THE SPRAY SWATH OF THE DC-3 FOR GYPSY MOTH SUPPRESSION USING *Bacillus thuringiensis*

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Introduction

Spray swaths for various aircraft were compared in a report entitled "Spray Swath Evaluation"(Teske et al.,1989). The basis of the comparison was the model AGDISP (AGricultural DISpersal). In the report, comparisons were made between AGDISP predicted spray swaths and those previously recommended by the USDA Animal Plant Health Inspection Service (APHIS) for aircraft spraying gypsy moth. The report showed a significant difference between the APHIS recommended swath width of 300 feet and AGDISP predicted swath width of 201 feet for the DC-3 spraying water. A re-examination of the numerical solution, with a sensitivity study of important field parameters was conducted again using AGDISP and reported in, DC-3 Sensitivity Study (1991, Appendix A) by Teske. This study evaluated key variables related to spray swath to determine conditions where swath width of the DC-3 could be increased. In the study, water was used as the test material. The study reconfirmed a difference in swath between APHIS recommendations and AGDISP predictions. With nozzle repositioning (moving nozzles outward on the boom), the study concluded that a maximum spray swath of 237 feet is possible when 8020 flat fan nozzles are used to spray 1 gallon per acre of water at a release height of 75 feet above the target.

The present study examines the spray swath of the DC-3 resulting from card data using the Swathkit (Bio-Aeronautical Technologies, Crystal Lake, IL) to read the cards and analyze results. To the extent possible, field tests were designed to confirm model results. Field observations consisted of three phases: 1) installation of radar altimeter for use in operational spraying, 2) use of Pathlink tracking system during operational spraying, and 3) spray card deposition data. Aircraft for this study were provided by K&K Aircraft of Bridgewater, Virginia. The study was done in cooperation with the Virginia Department of Agriculture and Consumer Services and the West Virginia Department of Agriculture.

Methods

The Sensitivity Analysis(AGDISP)

A sensitivity analysis of the DC-3 (Teske et al. 1991, Appendix A) was conducted using AGDISP. AGDISP is a computer model that predicts, as a function of time, the motion of particles or droplets released from an aircraft until they deposite on the target (Teske, 1988). It gives a single swath pattern prediction by combining the spray from each nozzle. Three droplet size distributions were examined for a base air speeds of 160 mph, and for variation of 150, and 140 mph. The sensitivity variations included: relative humidity of 40, 50, 60, 70 and 80 percent; Release height of 15.25 m (50 ft.), 30.49 m (100 ft), 45.73 m (150 ft), 60.98 m (200 ft), and 76.22 m (250 ft); wind direction to flight line of 15, 30, 45, and 90 degrees; and wind speed at 90 degrees to flight line of 0.89 m/sec (2 mph), 1.79 m/sec (4 mph), 2.24 m/sec (5 mph), and 2.68 m/sec (6 mph).

Treatment Observations

During operational spraying in Virginia, 1991, a Pathlink data recorder (Pathcore Inc., Tempe AZ) and radar altimeter (Terra Corp. TRI-40) were installed in a DC-3. The purpose was to check operational spraying altitudes and flight paths. The Pathlink system was used to record the location of the aircraft, its altitude, and when the aircraft's spray system was operating. Data recorded during this phase of the project were plotted and analyzed using an ARC-Info Geographic System (ESRI). Individual flight lines were plotted within block boundaries to simulate a 300 foot swath widths without any drift (Appendix B). The percent coverage by insecticide was calculated for individual blocks. The minimum, maximum, and average altitude of the aircraft was calculated when the spray boom was activated .

Swath Width Field Trials

Using information obtained from the sensitivity analysis and the operational suppression program, field trials were conducted in the Fall of 1991. The DC-3 was calibrated with undiluted B.t. (Foray 48B, Novo Laboratories) for a delivery of 64 ounces per acre at 160 mph and a swath width of 300 feet. The spray boom was equipped with twenty-six TeeJet 8020 nozzles with a boom pressure of 40 psi, resulting in a flow rate of 52.2 gal/min. Rhodamine WT, a visible tracer was added at a rate of 3 ml per liter of spray material.

Each characterization over-flight consisted of three parallel 500 foot cardlines, spaced 100 feet apart, and oriented perpendicular to the line of flight. Cardlines were initially laid out perpendicular to the wind direction, so the aircraft would fly into the wind. In addition, two card lines, termed variation lines, oriented parallel to the air-

craft's flight path were placed 50 feet on either side of the center line. Variation line data would reflect the level of variation in deposition at a specific distance from the centerline of the aircraft. This variation could be referenced to the atmospheric turbulence level collected at the time of the field trials. The evaluation of the variation in cardlines is located in Appendix C.

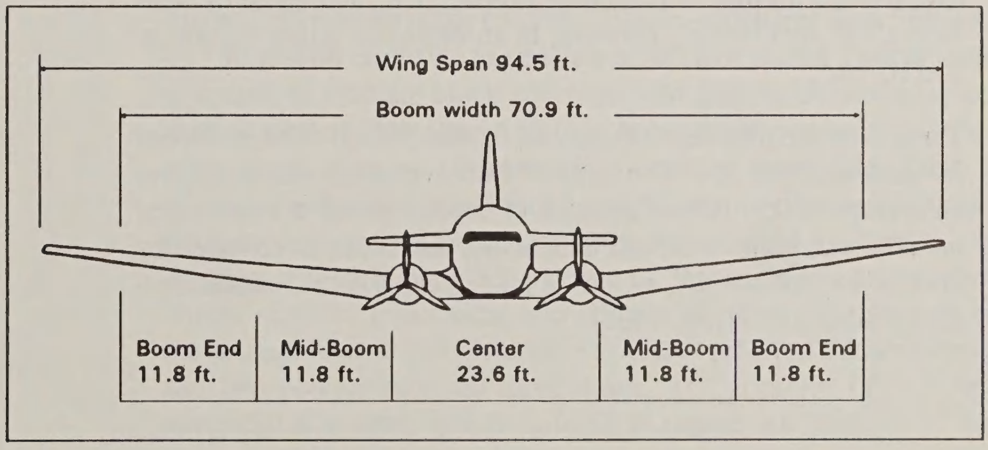
Kromekote cards (2 inches by 3 inches) placed horizontally on stakes 15 inches above the ground were used as collection surfaces for all cardlines. Aircraft height and position was recorded on the Pathlink recorder. The pilot was instructed to fly 100 to 125 feet above the card line during application. Aircraft speed during application was obtained using a radar gun. Environmental factors of wind direction, wind speed, relative humidity, and air temperature were recorded by the Swathkit at two second intervals for five minutes prior to and five minutes after the cardlines were over flown. The spray cards were left undisturbed for five minutes post spray. Cards were placed in protective boxes until read using the Swathkit image analyzer. An 0.9 spread factor was used when reading cards. This assumes almost no spread.

Aircraft spray booms were configured for five different scenarios.

In the first configuration (Initial) the boom was outfitted with twenty-nine, 8020 flat fan nozzles distributed across seventy-five percent of the boom. Flow rate of the undiluted B.t. was calibrated to be 52.2 gal/min.

In the second configuration (Extended) the boom was extended to 90 percent of the wing span. In this configuration, twenty-nine, 8020 flat fan nozzles were again used. This time, however, nozzles were removed from the belly section and moved outward on the boom. Flow rate was calibrated to be 52.2 gal/min.

Figure 1. Boom dissection for the DC3; to evaluate spray deposit contributed from nozzles placed at each segment of boom (center, mid-boom, and boom end).



In the last three scenarios, nozzle configuration was designed to dissect the spray boom in order to evaluate nozzle placement and resulting spray pattern (see Figure 1). Three boom dissections were used; the first configuration had fifteen, 8020 flat fan nozzles located only on the center portion of the boom which resulted in a flow rate of 27 gal/min; the second configuration had twenty, 8020 flat fan nozzles located only on the mid-section of each boom which resulted in a flow rate of 36 gal/min; and, the third configuration had twenty-four, 8020 nozzles located on the third segment of each boom which resulted in a flow rate of 43.2 gallons per minute.

Data Analysis

Deposition from the three card lines for each over flight were averaged together to provide the deposition for each card position. The Swathkit was used to analyze these card lines to determine average number of droplets per square centimeter, dose as expressed in international units of B.t. per square centimeter, and the coefficient of variation (COV) for the deposition pattern. COV is defined as the sample standard deviation expressed as a percentage of the mean. It is a relative measure of variation in the data.

In order to determine effective swath width, the target volume that will give effective control must be determined. In a laboratory study, Bryant and Yendol (1988) determined the lethal dose for a B.t. concentration of 4,227 IU/µl (12 BIU/Ac) for three different droplet sizes. They suggested that increased dose was required with increase in drop size. The LD_{95} (lethal dose for 95 percent of the population) for 100, 200, and 300 micron drops was 23.9, 38.4, and 52.8 IU/cm^2, respectively. If we assume that for every acre of land there are 5 acres of leaf surface, then five times the IU/cm^2 would be required to give effective control (Bryant and Yendol, 1988). Average volume median diameter (VMD) of droplets anticipated for this spray system was 200 - 300 microns. To be conservative, the upper range of dose was chosen, 52.8, multiplied by 5 (to reflect leaf area factor), resulting in an estimated target volume of 250 IU/cm^2.

Three lane separations, 200 ft, 250 ft, and 300 ft, were evaluated for each averaged line. The basis of each evaluation was to achieve an average of 250 IU/cm^2 volume of deposit across the swath and minimal variation in deposit data across the swath as reflected by the COV. For this study, a COV of 30 percent is considered acceptable (Parkin and Wyatt, 1982).

Results

Pathlink/Radar Altimeter Results

Altimeter readings were recorded on a total of eight flights whereby 21 separate blocks were treated. Table 1 gives a listing of minimum, maximum, and average altimeter readings during treatment for all altimeter readings during treatment. Figure 2 shows a plot of 6 treatment blocks, flight lines, and corresponding altimeter reading for each block.

Table 1. Altitude readings expressed in feet for the DC3 during operational treatment for gypsy moth control.

FLIGHT	MINIMUM	MAXIMUM	AVERAGE
CUL430	92	188	128
CUL51	84	176	127
CUL51B	98	190	140
FR53	70	222	130
FR53A	58	224	120
PRWM51	112	284	157
PRWM52	94	268	150
PRWM53	88	222	141
All Flights	58	284	137

Altimeter readings indicate that the average DC-3 altitude during treatment was above the contract specified height of 100 feet. The size and speed of the DC-3 along with the variation in terrain within the treatment blocks probably accounts for much of this increase in altitude. In addition the canopy in early spring with small leaflets does not reflect radar as well as a fully developed canopy. Signal penetration below the canopy top would indicate the aircraft was higher than its actual spraying altitude.

Figure 3 shows one of the treatment blocks with flight lines buffered by 150 feet on each side to simulate a 300 foot swath. This process was used to evaluate block coverage with insecticide assuming no drift. A total of 15 treatment blocks (Appendix B) was used to evaluate percent coverage of treatment blocks by insecticide. Table 2 shows individual and total block acreage, amount of insecticide coverage by acre, and the percent of block that received insecticide. On average, approximately 65 percent of the acreage in treatment blocks received insecticide, excluding drift. Forty-four percent of the acreage receive a single dose, 18 percent received a double dose, and two percent received three doses. The accuracy of LORAN navigational system, which is used to record the position of the

Figure 2. 1991 treatment blocks with DC-3 flight paths overlaid. Each block corresponds to an altimeter recording from which actual treatment heights were determined.

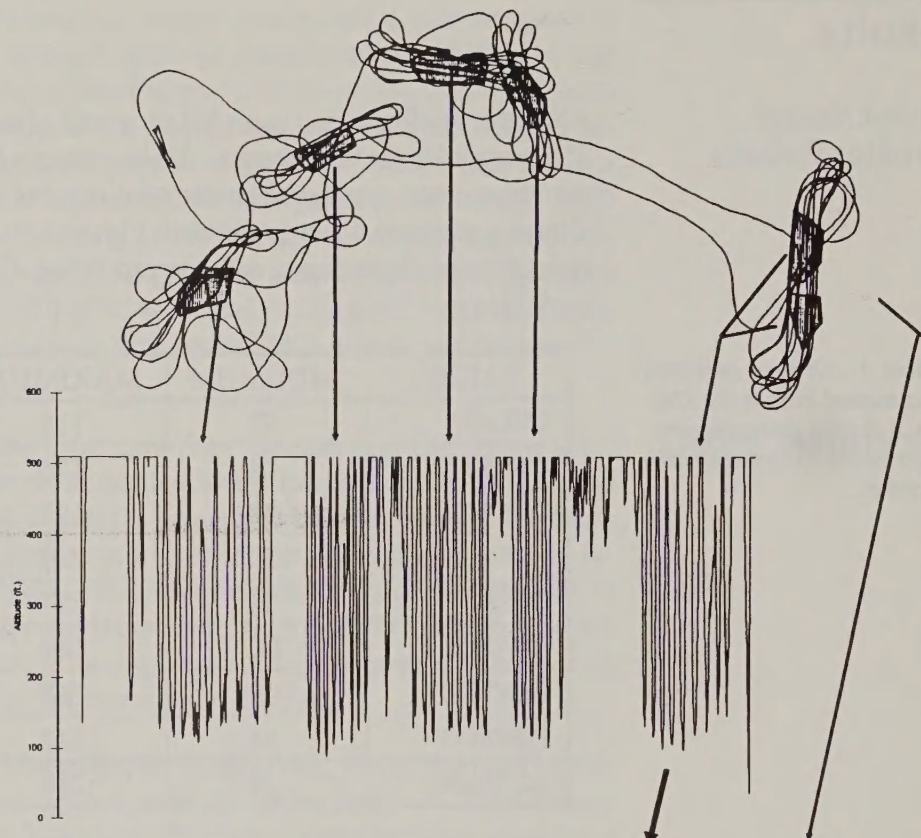
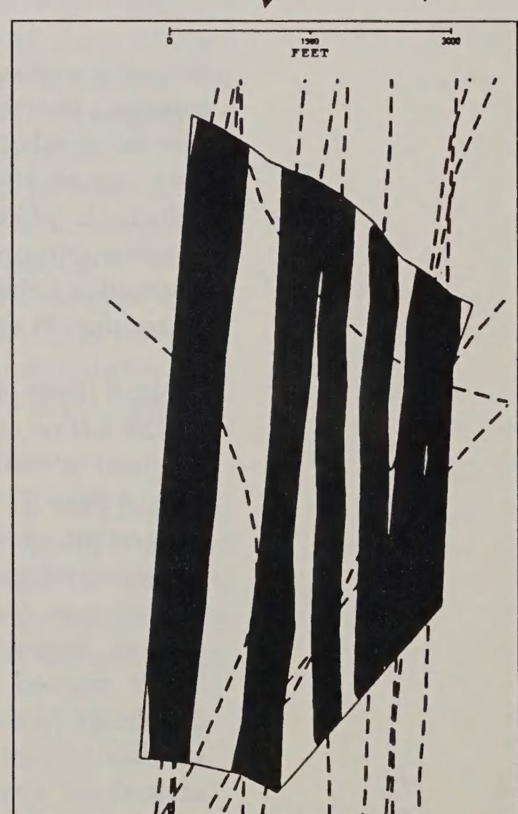


Figure 3. Treatment block, with flight lines buffered by 300 ft to simulate area covered by insecticide. At this swath approximately 70 percent of the block received insecticide.



aircraft, is not exact. Therefore, plots of flight lines may not represent the true flight path. Flight lines may be either closer together or further apart than those that were recorded. By averaging all flights together, some of this variation can be minimized. This percent coverage is similar to that recorded for a Bell 206 III helicopter by the USDA Forest Service during a 1989 eradication project (Ghent, unpublished data). It is interesting to note that the size of the block did not seem to affect percent coverage. The average of the four largest blocks had only four percent more coverage than the average of the four smallest blocks.

Table 2. Percent insecticide coverage for individual treatment blocks. Coverage based on a 300 foot swath.

Block Number	Total Acres	Percent of Block Acreage Recieving: 1 Dose	2 Doses	3 Doses	None
CUL51C	147	52	12	0	35
FR53B	199	44	39	1	16
PRM53F	280	42	17	0	40
PWM53B	285	32	11	1	56
PWM53D	318	44	12	0	44
PWM53E	403	44	23	1	32
PWM53C	471	45	13	4	38
PWM52A	483	43	23	2	32
CUL51B	867	40	32	7	20
CUL51E	867	48	9	0	37
PRM52C	899	45	18	3	33
FR53A	1441	42	27	6	25
FR53C	1855	45	15	2	38
CUL51D	1989	46	12	0	42
AVERAGE	750	44	18	2	35

Spray Card Results

Recovery of spray deposit on the Kromekote cards as determined by the Swathkit averaged forty-nine percent of material released from the aircraft. Reardon et al. (1990) showed that horizontally placed flat cards are poor collectors of droplet density but better collectors of volume per unit area particularly in low winds. This is probably due to the horizontal collectors not capturing the small drops as well as they do the larger drop sizes.

In this analysis, mass per unit area is used as the primary evaluation method. This measure is calculated from volumes of deposit. Mass per unit area reported here is undoubtedly lower than if more efficient collectors had been used, though how much lower is unknown.

VMD's reported here are undoubtedly somewhat larger than would be expected with more efficient collectors of small drops.

I Flight Lines

The initial configuration had nozzles evenly distributed across the boom, extending to seventy-five percent of the wing length. Table 3 shows the environmental and operational conditions for the overflights. Two separate flights are summarized for the initial configuration. Summaries represent the average of three cardlines for each of the two flights.

Table 3. Environmental and operational parameters present during card line over flights of I1 and I3.

Parameters	I 1	I 3
Altitude (feet)	125	125
Air Speed (mph)	166	167
Average wind speed (mph) for 10 minutes	1.4	2.3
Wind speed at time of release (mph)	4	1
Line orientation (degrees)	200	200
Average wind direction (degrees)	114	236
Average temperature (F^0)	64	65
Average relative humidity (percent)	75	70

The difference between I1 and I3 consists primarily of differences in wind direction relative to cardline orientation. The crosswind effect in I1 can be seen in Figure 4, while an into the wind effect in I3 can be seen in Figure 6.

The single spray pattern for the I1 cardlines is shown in Figure 4 (IU/cm^2) and Figure 5 (drops/cm^2). Note that the entire pattern extends approximately 280 feet. The pattern has an average deposit volume of 306 IU/cm^2 and a VMD of 319 microns. Droplet density,

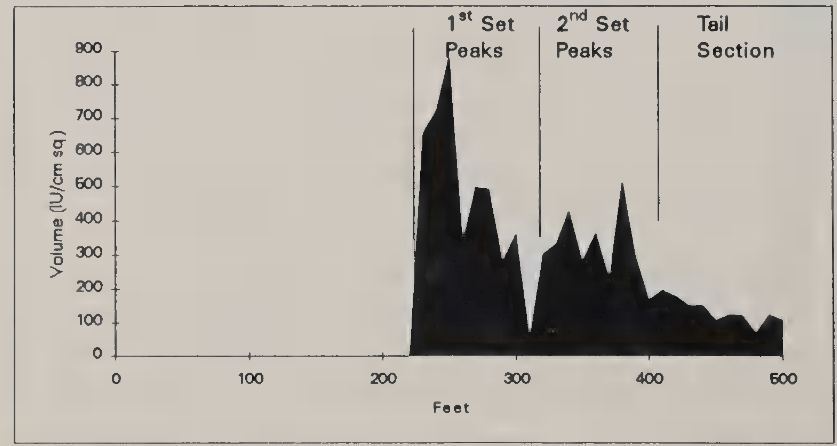


Figure 4. Flight line I1, average deposition for three card lines, expressed as IU/cm^2.

as shown in Figure 5, averages 7 drops per square centimeter across the pattern. For analysis purposes, the pattern in Figure 4 can be divided into 3 components (Table 4) based upon visual observation of the pattern.

Table 4. Flight I1 spray pattern analysis for Figure 4.

Swath Section	IU/cm^2	Drops/cm^2	VMD (μ)
First Set of Peaks (80 ft.)	525	8	361
Second Set of Peaks (80 ft.)	313	7	363
Tail End of Swath (120 ft.)	137	8	233

Although the tail of the pattern has a high droplet density, total volume of deposit is below the desired 250 IU/cm^2. Effective use of the aircraft with this type of pattern is simulated with a racetrack flight pattern, as illustrated in Figure 7, with the first series of peaks overlapping the tail. Of the three lane separations simulated for I1, 200 feet produces an average deposit volume closest to the target while minimizing coefficient of variation.

The I3 cardlines are summarized in Figure 6 for single spray patterns. Here, the direction of flight is almost directly into wind. Two differences from the crosswind pattern (Figure 4) are evident; 1) the horizontal deposition pattern is wider and 2) the pattern is distinctly bimodal, that is, two peaks are evident.

The length of the pattern in Figure 6 is 350 feet with an average volume deposition of 253 IU/cm squared. The pattern can be divided into three sections as shown in Table 5.

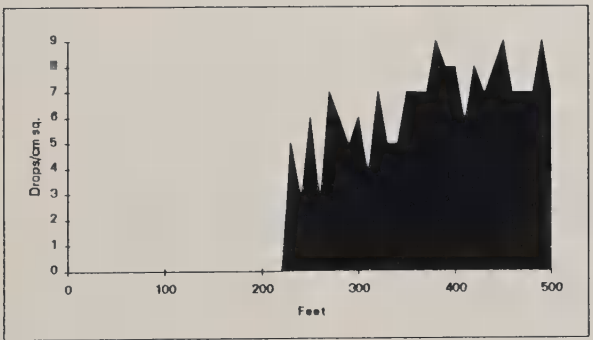


Figure 5. Flight I1, average deposition, expressed in drops/cm^2.

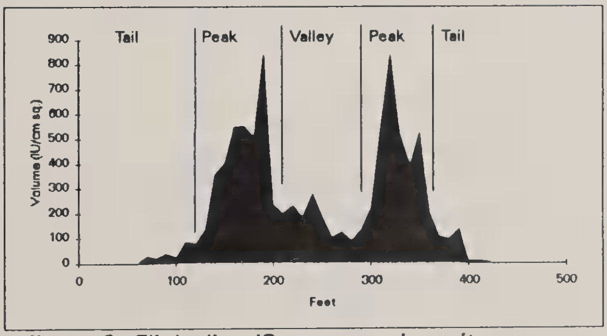


Figure 6. Flight line I3, average deposit expressed as IU/cm^2

Swath Section	Volume (IU/cm^2)	Drops/cm^2	VMD (μ)
Two Tails (120 ft.)	62	6	152
Two Peaks (160 ft.)	448	11	299
Valley (70 ft.)	161	8	263

Table 5. I3 Spray Pattern analysis for Figure 4.

The into wind flight pattern produced a wider effective swath than the crosswind flight pattern. Similar results were reported by Teske (1991, reproduced in Appendix A). Teske attributed the difference to the crosswind arresting the upwind motion of the vortex, while into wind the vortex helps spread the pattern in both directions. Notice the difference in VMD in the above tables between the "tails" of I3 and I1. In I1, size of drops deposited in the tail is quite large indicating that the fine droplets have continued downwind and off the cardline. In I3 the fine droplets are caught within the vortices and are forced down, forming the tails. Flying the aircraft into the wind helped maximize droplet capture and minimize small droplet drift.

AVERAGE DEPOSIT					
FILENAME	AVGE1	IU/CM SQ...	351.2	COV........	37.3
ACTION..	Overlap	DROPS/CM SQ		Recovery...	
FLIGHT..	Racetrack	V.M.D......		Range... 115.0	646.0
LANE....	200	Perc. Area.		Cross wind.	1.8

OVERLAP SIMULATION

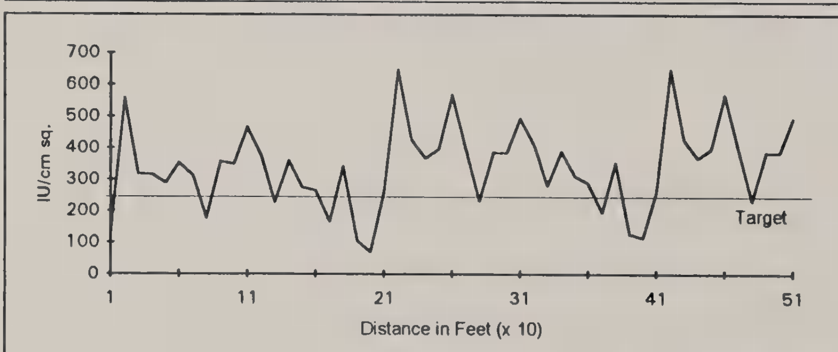


Figure 7. Swathkit overlap simulation of E1, using a 200 foot lane separation.

E flight lines

The "E" flights utilized extended boom and vortex decay panels on each wing. The purpose was to move nozzle placement outward on the wings and to observe the effect of vortex decay panels upon the shape and distribution of the spray pattern. Three flights were made over three cardlines each and these are summarized in Table 6.

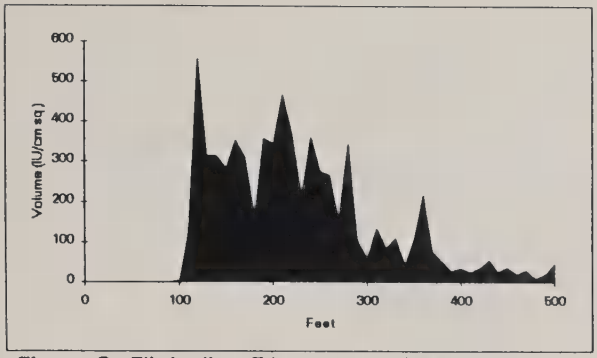


Figure 8. Flight line E1, average deposition, expressed in IU/cm^2.

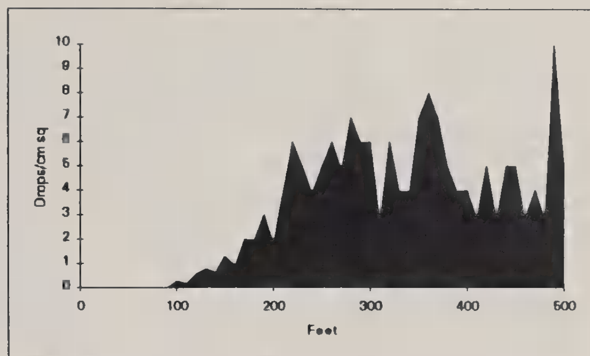


Figure 9. Flight line E1, average deposition, expressed in $drops/cm^2$.

Table 6. Environmental and operational parameters present during card line over flight of extended boom flight lines.

Parameters	E1	E2	E3
Altitude (feet)	125	50	50
Air Speed (mph)	158	158	161
Average wind speed (mph) for 10 minutes	6.3	6.9	6.7
Wind speed at time of release (mph)	4.0	4.2	7.0
Line orientation (degrees)	150	150	150
Average wind direction (degrees)	233	203	214
Average temperature (F0)	59	60	62
Average percent relative humidity	68	66	61

In Table 6 comparisons can be made between E1 and E2 for the effect of altitude, 125 feet versus 50 feet, since both are into wind. Wind speeds were similar for each flight with the exception that E3 had the highest wind speed immediately at the time of deposit.

Single spray patterns for the averaged E1 flight are shown in Figures 8 and 9. These patterns are more typical of crosswind effects, and the reduction in bimodal peaks may be due to extending the boom and the influence of the vortex decay panels. These figures illustrate that the heavy deposit immediately beneath the aircraft consists of a small number of large drops. Across the entire pattern droplet density averaged 4 $drops/cm^2$, with the highest droplet densities deposited downwind. The first 100 feet of the pattern had an average deposit volume of 286 IU/cm^2 and an average droplet density of 1.3 $drops/cm^2$; the next 210 feet had an average deposit volume of 210 IU/cm^2 and an average droplet density of 5.4 $drops/cm^2$; and the next 140 feet had an average volume deposit of 29 IU/cm^2 and an average droplet density of 6 $drops/cm^2$. In this pattern, target volumes were achieved in the first 100 feet of the pattern, and then only

in a relatively few large drops. Results are summarized in Table 7.

Flight	Wind Direction	Drops/cm^2	Vol(IU/cm^2)	VMD(μ)	NMD(μ)
E1	Into Wind	4	171	305	125
E2	Cross Wind	6	312	261	118
E3	Cross Wind	4	172	230	82

Table 7. Summary of extended boom (E) deposition results.

E2 and E3 were both flown at 50 feet above the cardlines. Single spray patterns for E2 and E3 flights are shown in Figure 10 and 11, for volumes (IU/cm sq.). The bimodal effect created by the wing tip vortices is somewhat absent in these crosswind examples. This may be a result of the extended boom.

Evaluation of three lane separations were made using Swathkit. Simulations were run for all the averaged flight lines and the results are displayed in Table 8. These results indicate that lane separations between 200 and 250 feet represent the best compromise between minimizing COV while coming closest to the target volume. Obtaining volumes closest to the target can only be obtained with relatively high pattern variation as reflected by the coefficient of variation.

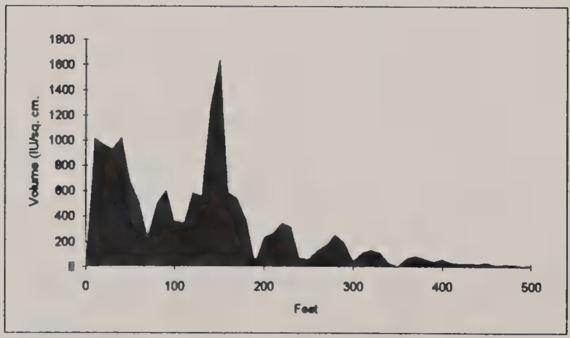


Figure 10. Flight line E2, average deposition, expressed in IU/cm^2

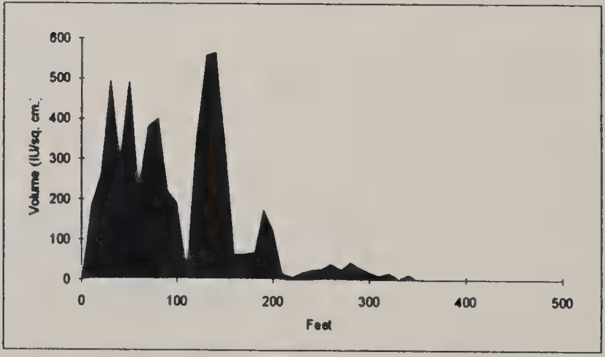


Figure 11. Flight line E3, average deposition, expressed in IU/cm^2

Table 8. Results of simulated swath widths for all average E and I flight lines.

Flight Lines	Simulated Lane Separations					
	200 feet		250 feet		300 feet	
	COV	IU/cm^2	COV	IU/cm^2	COV	IU/cm^2
I1	56	428	67	343	74	286
I3	67	455	59	364	71	303
E1	38	346	52	277	63	231
E2	51	797	66	637	76	531
E3	57	292	78	226	91	195

Boom Dissection

Nozzles were configured at three boom locations in order to assess the contribution of each boom segment to overall swath pattern. The three sections are; center or belly of the aircraft, mid-boom, and boom-end. Results are summarized in Table 9 where deposit data was averaged for the three card lines encompassing each flight.

The results indicate that the heaviest deposit occurs from the center configured nozzles. This is true for both volume of deposit and numbers of drops. As shown in Figure 13, the deposit from the center configured nozzles is relatively unaffected by wing vortices. The spray cloud remains intact, clustered, and is shifted either to the right or left depending upon wind force and direction. This is contrasted to the patterns resulting from the mid-boom (Figure 14) and boom-end (Figure 15) configurations in which the spray cloud is distributed over a larger area with peaks and valleys similar to patterns resulting from the influence of wing-tip vortices. Interestingly, both the mid-boom and boom-end nozzle configurations show a deposit pattern extending across the width of the aircraft. In addition, VMD's are somewhat smaller for drops originating from the mid or end boom nozzle positions. This indicates that nozzles located at mid-boom and boom-end contribute to the overall widening of the spray pattern more so than do center located nozzles.

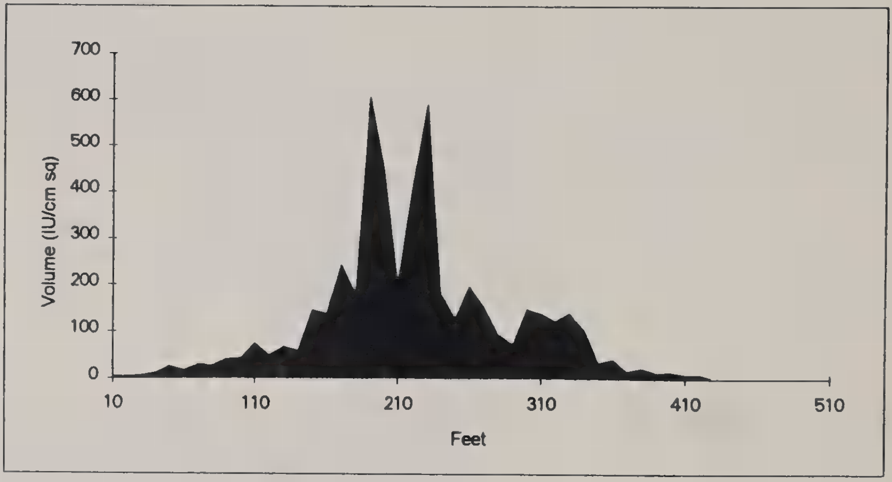


Figure 13. Deposit expressed in IU per centimeter square for nozzles placed only on the center one third of the spray boom.

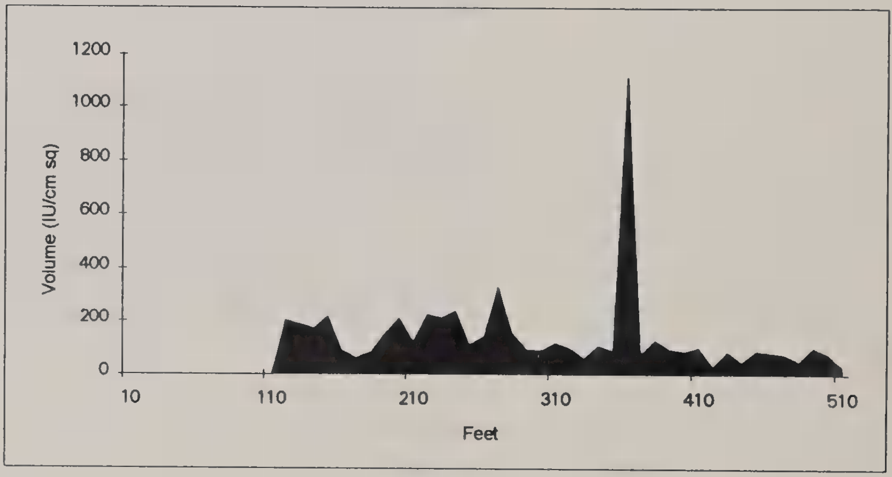


Figure 14. Deposit expressed in IU per centimeter square for nozzles placed only on the middle one third of the spray boom.

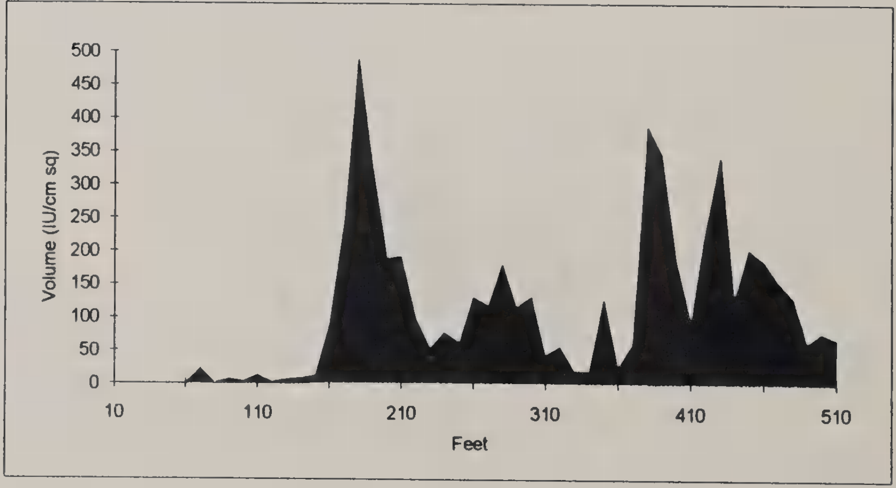


Figure 15. Deposit expressed in IU per centimeter square for nozzles placed only on the outer one third of the spray boom.

Table 9. Results of boom dissection. Location and dimentions of boom sections are shown in Figure

Flight Line	Volume (IU/cm^2)	Drops/cm^2	VMD (µ)
Boom End			
1	163.6	2.4	309
2	116.4	3.2	222
3	126.4	4.3	231
Average	135.5	3.3	254
Mid-Boom			
1	115.0	2.8	255
2	119.9	4.9	208
Average	117.5	3.9	232
Center of Boom			
1	118.4	2.6	237
2	784.8	7.5	351
3	572.4	5.7	313
4	124.2	6.1	194
5	300.4	5.6	263
Average	380.4	5.5	272

Summary

The cardline data showed that when using undiluted B.t. and a target dose of 250 IU's/cm square an acceptable spray swath for the DC-3 is between 200 and 250 feet . Taken as a whole, the results of cardlines, variation lines, and AGDISP, a spray swath of 225 feet is recommended.

For B.t., crosswind spraying decreases the usable spray pattern. Small droplets which have little volume, and therefore dose, drift off target under crosswind conditions and do not contribute a significant number of IU's to adjacent swaths.

Widening the swath width is best achieved through moving nozzles outward toward the mid and end boom. The extended boom appears to have reduced the bimodal spray pattern. However, it did not significantly increase spray swath. Boom length should be kept at seventy-five percent of the wing span (70.9 feet). This will prevent the loss of small droplets in the wing-tip vortices.

Droplet sizes resulting from the use of 8020 flat fan nozzles spraying undiluted B.t. averaged near 270 microns (VMD). This estimate is probably higher than if vertical collectors had been added to the cardlines and smaller droplets recovered.

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Acknowledgments

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Appendix A

DC-3 Sensitivity Study

C. D. I. Technical Note No. 91-06

DC-3 SENSITIVITY STUDY

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1. SUMMARY

Continuum Dynamics, Inc. has completed a sensitivity study of several key variables affecting the deposition of released spray material into the wake of a DC-3 aircraft. The numerical approach utilized the latest version of the USDA Forest Service computer product AGDISP to form a linear analysis around a nominal, or base case, parameter set.

For the most part trends in the results may be explained on a physical basis; however, the worth of the present analysis is its quantification of the relative sensitivity of the results to known input variable changes.

The most important result, unfortunately, is that significant changes in input parameters lead to small changes in desired output. Swath width is relatively unchanged from its previous AGDISP prediction except by repositioning boom nozzles to extend the edges of the ground deposition pattern.

2. APPROACH

This report summarizes a sensitivity study of several key variables input into the USDA Forest Service computer product AGDISP Mod 6.0 (Ref. 1). Its stated purpose is to determine, if possible, conditions where the swath width of the DC-3 can be increased to a more desirable value from the value reported in earlier computer simulations (Ref. 2).

In the previous report (Ref. 2) swath width comparisons were made between the generally accepted APHIS guidelines and AGDISP predictions. Surprisingly, one aircraft, the DC-3, exhibited a significant difference between the guidelines and the predictions. APHIS guidelines for the DC-3 suggest a swath width of 91.5 m (300 ft), while AGDISP predictions for the same aircraft suggest 61.3 m (201 ft). A re-examination of the numerical solution, with a sensitivity study of important field parameters, was considered in order.

The nominal, or base case, parameter set is shown in Table 1. The aircraft inputs were recovered from Ref. 2 with the correct planform area. The aircraft weight was taken to be its empty weight plus one-half its useful payload weight. Nozzles were initially distributed uniformly along the breadth of the boom (49 nozzles in the base case). The canopy was considered simple ground cover without interfering structure.

Three drop size distributions are examined in the present study (Table 2 and Figure 1): for the base case air speed of 160 mph, and for variations of 150 and 140 mph. The drop size distributions were obtained from the USDA Forest Service database (Ref. 3) with the DROPSIZE program (Ref. 4).

AGDISP predictions are shown in Figure 2 (number density), Figure 3 (mass) and Figure 4 (coefficient of variation). In all cases ground deposition results were computed at three-meter intervals between -100 meters upwind and 200 meters downwind.

The sensitivity study variations are summarized in Table 3. In all cases the analysis is linear; that is, a single variable is changed from the base case. The principal computed variable of interest is the swath width.

Table 1
DC-3 Sensitivity Study Base Case Parameter Set

Aircraft type	DC-3
Weight	95,175 N (21,395 lbs)
Wingspan	28.82 m (94.5 ft)
Planform area	93.79 sq m (1,009.0 sq ft)
Drag coefficient	0.1
Propeller radius	1.77 m (5.8 ft)
Engine efficiency	0.8
Propeller blade rotation rate	2,550 rpm
Propeller locations	6.10 m (20.0 ft) forward of boom 2.90 m (9.5 ft) lateral of centerline -1.22 m (-4.0 ft) vertical of boom
Volume flow rate	97.0 gal/min
Nozzle type	8020 flat fan at 90 deg
Volatile fraction	0.984
Air speed	71.54 m/sec (160.0 mph)
Release height	22.87 m (75.0 ft)
Boom length	0.75 (fraction of wingspan)
Temperature	61.0 deg F
Relative humidity	64.0 percent
Wind speed	1.34 m/sec (3.0 mph) in-wind at 15.24 m (50 ft)

Table 2
DC-3 Sensitivity Study Drop Size Distributions

Size µm	160 mph	150 mph	140 mph
45.88	0.0121	0.0115	0.0107
73.73	0.0295	0.0274	0.0248
106.35	0.0558	0.0521	0.0474
138.62	0.1259	0.1180	0.1078
171.03	0.1767	0.1649	0.1499
203.95	0.1824	0.1674	0.1491
235.88	0.1846	0.1698	0.1516
268.32	0.0800	0.0843	0.0871
301.32		0.0267	0.0468
334.77	0.0346	0.0435	0.0518
366.72			0.0202
398.21		0.0145	0.0213
430.71	0.0291	0.0358	0.0419
463.18	0.0419	0.0422	0.0417
495.68			
528.67	0.0334	0.0325	0.0310
Total:	0.9860	0.9906	0.9831
VMD	204.5 µm	211.1 µm	221.2 µm

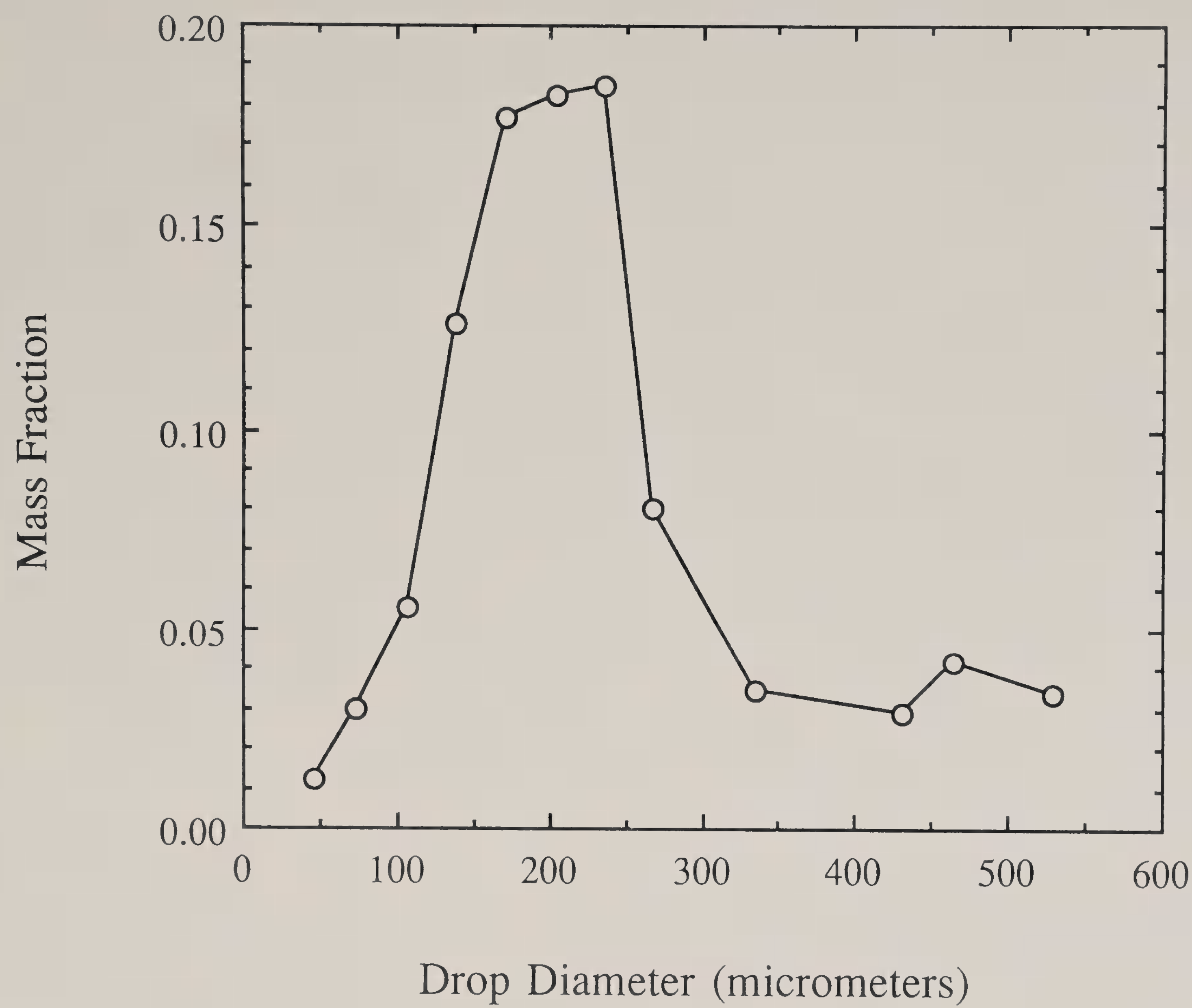


Figure 1. Base case drop size distribution.

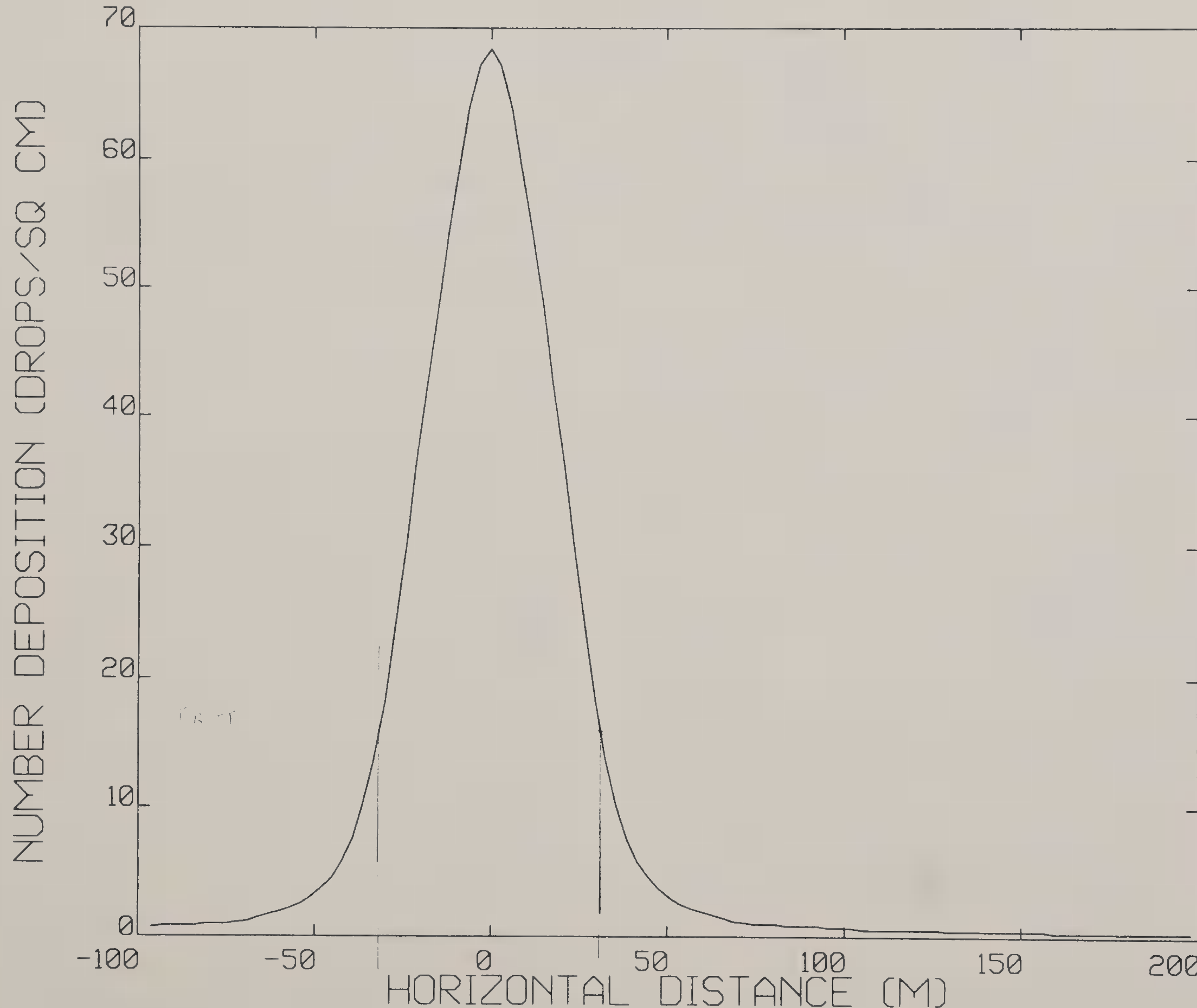


Figure 2. Base case ground deposition pattern for number density.

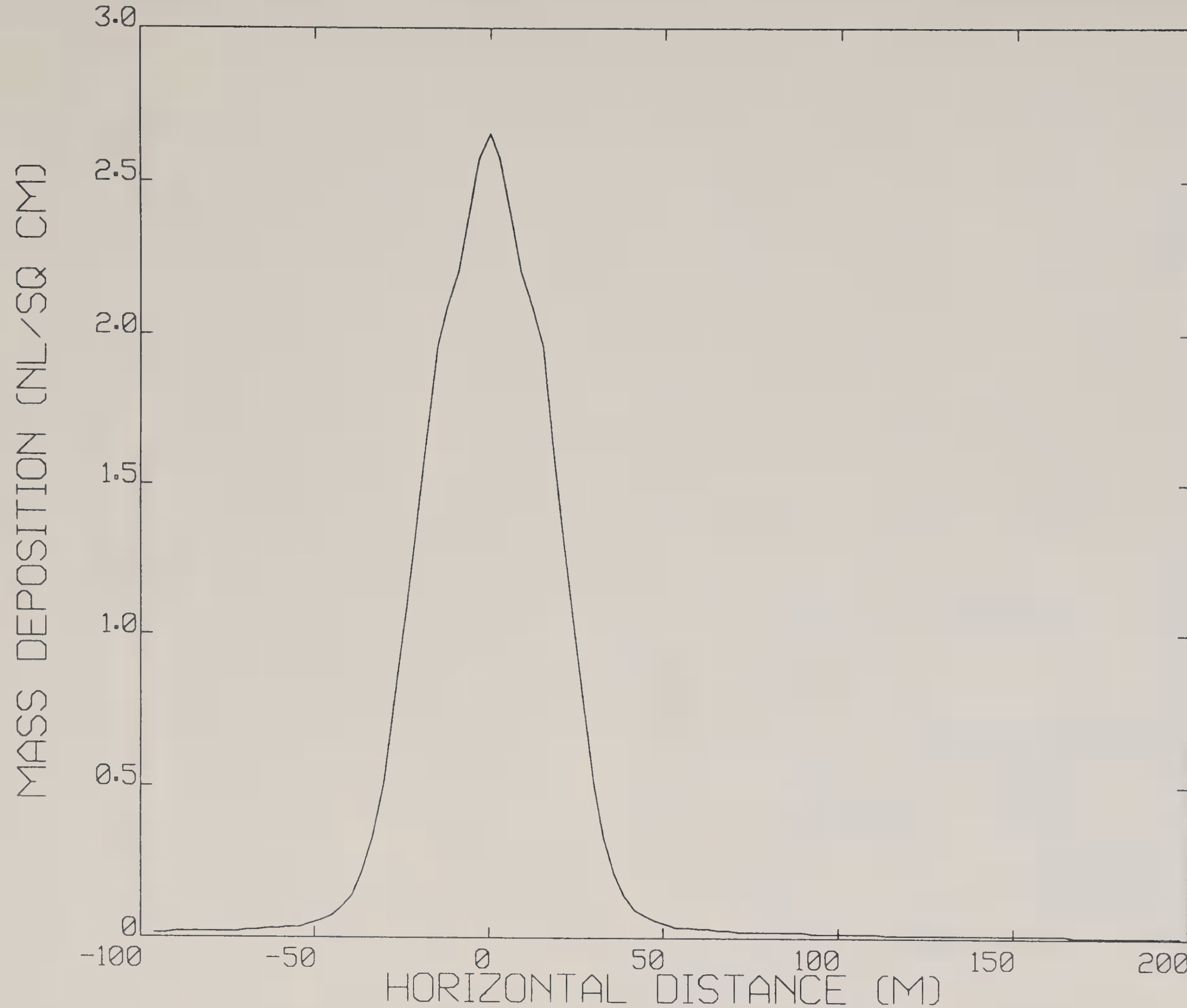


Figure 3. Base case ground deposition pattern for mass.

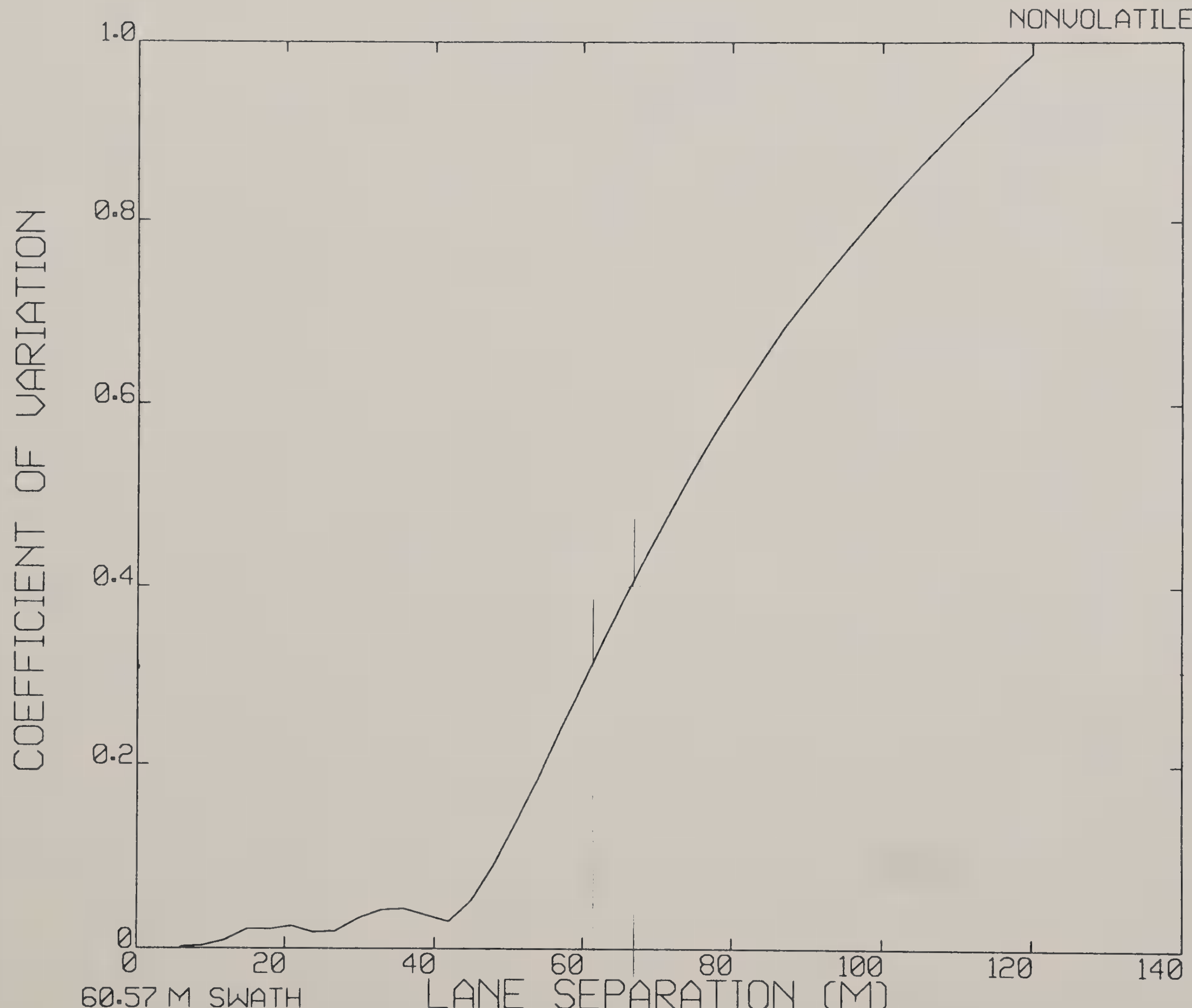


Figure 4. Base case coefficient of variation effect with lane separation (swath width). A best value at COV = 0.3 is 60.57 m (199 ft).

Table 3
DC-3 Sensitivity Study Input Variables and Ranges

Relative Humidity	40, 50, 60, 70 and 80 percent
Release Height	15.25 m (50 ft) 30.49 100 45.73 150 60.98 200 76.22 250
Air Speed	67.07 m/sec (150 mph) 90.91 gal/min (45 nozzles) 62.60 m/sec (140 mph) 84.85 gal/min (43 nozzles)
Wind Direction	15, 30, 45 and 90 deg
Wind Speed at 90 deg	0.89 m/sec (2 mph) 1.79 4 2.24 5 2.68 6

Nozzles at 90 percent of wingspan

Nozzles repositioned with and without fuselage interference

3. RESULTS

Sensitivity variations are shown in Figure 5 and following for the variations described in Table 3:

Relative Humidity (Figure 5) is not a very significant variation because the base case temperature (61 deg F) permits nearly complete evaporation of the released spray material. Both trends are correct: as the relative humidity decreases, more material evaporates, less material deposits, and the average number density and swath width decrease.

Release Height (Figure 6) shows predictable trends as well: as the release height increases, the deposited material is spread over a larger area, decreasing the average number density and increasing swath width. At the higher release heights the average number density falls below the anticipated minimum acceptable level of 15 to 20 drops per square centimeter (Ref. 2).

Air Speed (Figure 7) affects three model inputs: the strength of the wingtip vortices (inversely proportional), the volume flow rate (directly proportional), and the number of nozzles. As the air speed decreases, the volume flow rate (in gal/min) decreases, and less material deposits (the trend is in fact a linear one in the AGDISP predictions). Swath width remains relatively unchanged. For the parameters chosen here, complications because of a modification to the vortex strength are not present (in some cases released spray material may move to completely different locations and make interpretation difficult).

Wind Direction (Figure 8) demonstrates an interesting result: the importance of in-wind spray release. As wind direction changes from in-wind, a significant reduction occurs in swath width. It may be surmised that the crosswind component arrests the outward motion of the vortex on the upwind side, thereby enabling the released spray material to deposit before moving upwind. The base case and crosswind ground deposition patterns are compared in Figure 9.

It may be instructive at this point to examine different crosswind speeds in an attempt to recover the base case swath width in a crosswind situation. Limits on this sensitivity are the minimum and maximum observed wind speeds at previous gypsy moth spray projects in the Northeast. Wind Speed results (Figure 10) demonstrate the effects of crosswind on drift. Average deposition decreases as the wind speed increases, while drift permits swath width to increase. Only near the upper limit of the wind speed is the base case swath width recovered. Ground deposition patterns may be examined to recover the volume-averaged mean location, measured downwind relative to the aircraft centerline. This variable (Figure 11) quantifies the drift of the released spray material with wind speed. It is interesting to note that 60 meters is the approximate swath width; a crosswind of six mph moves spray deposition lines one swath width downwind.

Unfortunately, none of these simple variations appreciably increases the swath width of the DC-3. Figure 12 illustrates the trajectories of the released spray material from the 8020 flat fan nozzles to the ground. Two interesting features may be noted:

1. The concentration of trajectories near the aircraft centerline (due to the propeller engines).

2. The wide spread of the outermost trajectories near the ground (due to the wingtip vortices).

Three nozzle distributions were developed to take advantage of these insights:

1. Nozzles uniformly distributed out to 90 percent of the wingspan.

2. Nozzles repositioned from near the center of the aircraft to near the outer ends of the boom.

3. Nozzles additionally removed from under the center of the aircraft and repositioned near the inner ends of the boom.

Not surprisingly (Figure 13), the longer boom gives a wider swath at the expense of lower material deposition. The result for the 90 percent case, however, does not illustrate the added drift potential from spray material entrainment into the wingtip vortices (an effect evident in smaller dropsize trajectories).

Nozzle repositioning appears to give the best chance of increasing swath width, although at the expense of lower spray material deposition levels. Figure 14 compares the ground deposition pattern from nozzle repositioning with the base case results.

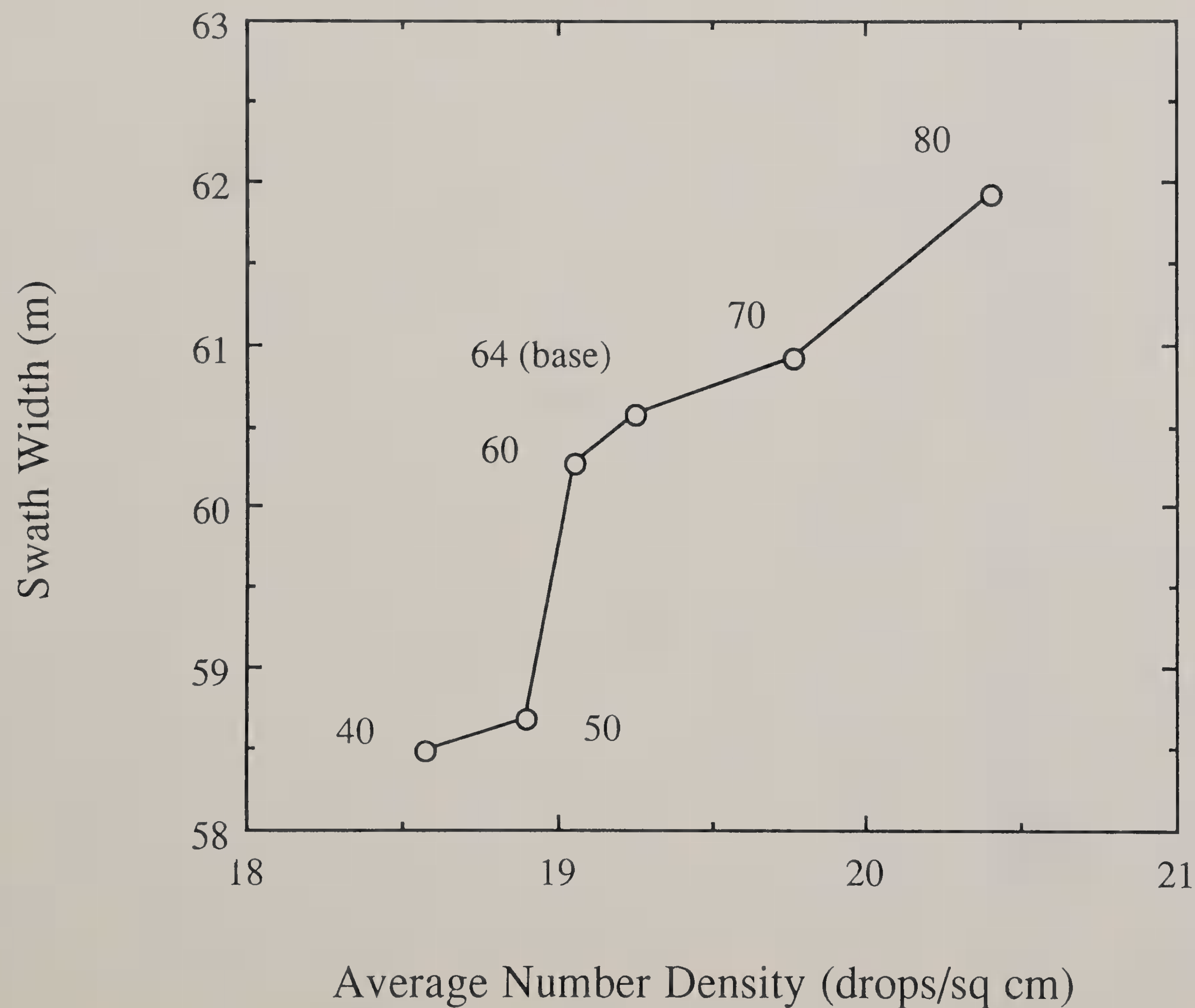


Figure 5. Sensitivity of the average (overlapped) number density and swath width to changes in relative humidity (in percent as indicated).

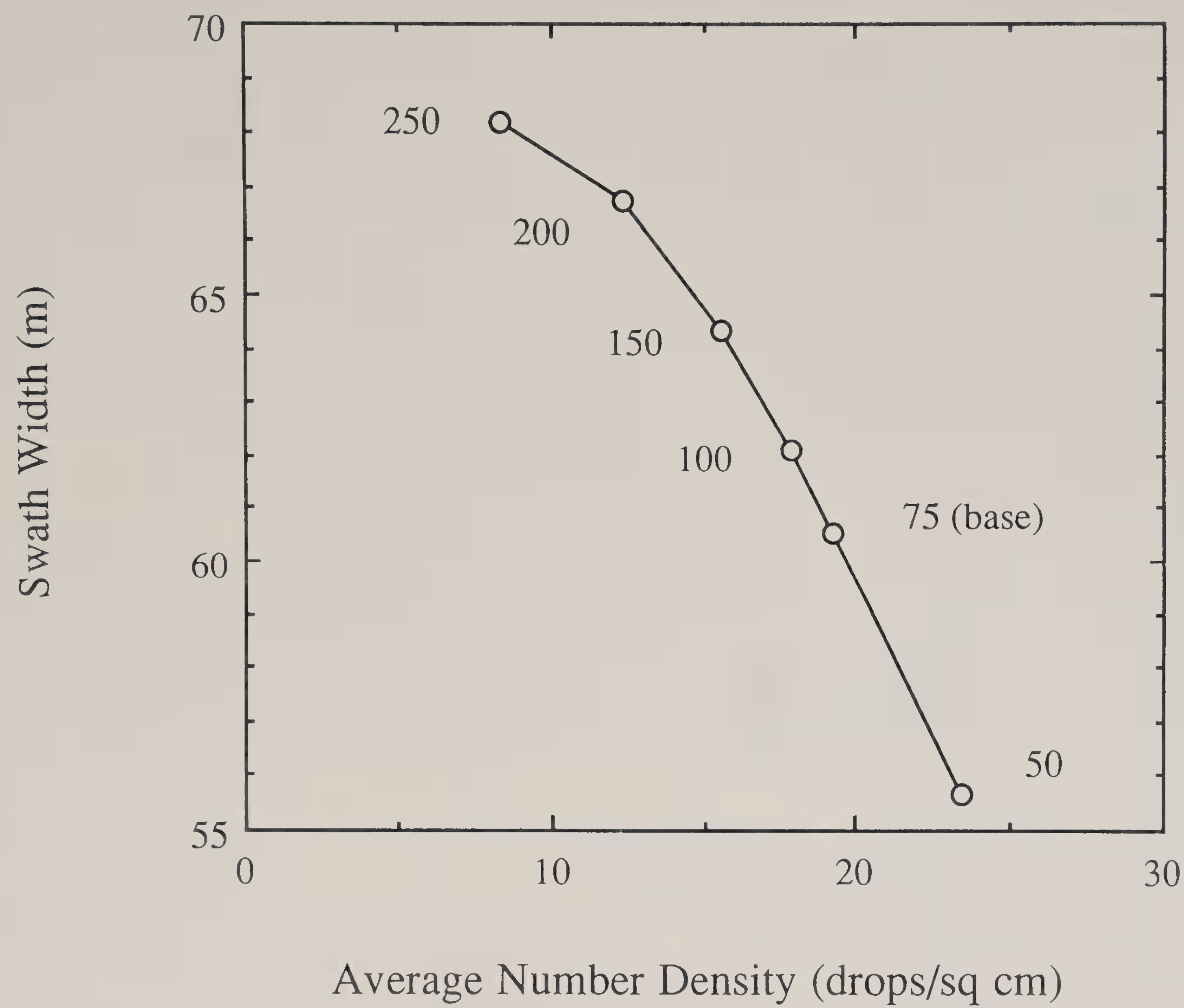


Figure 6. Sensitivity of the average (overlapped) number density and swath width to changes in release height (in feet as indicated).

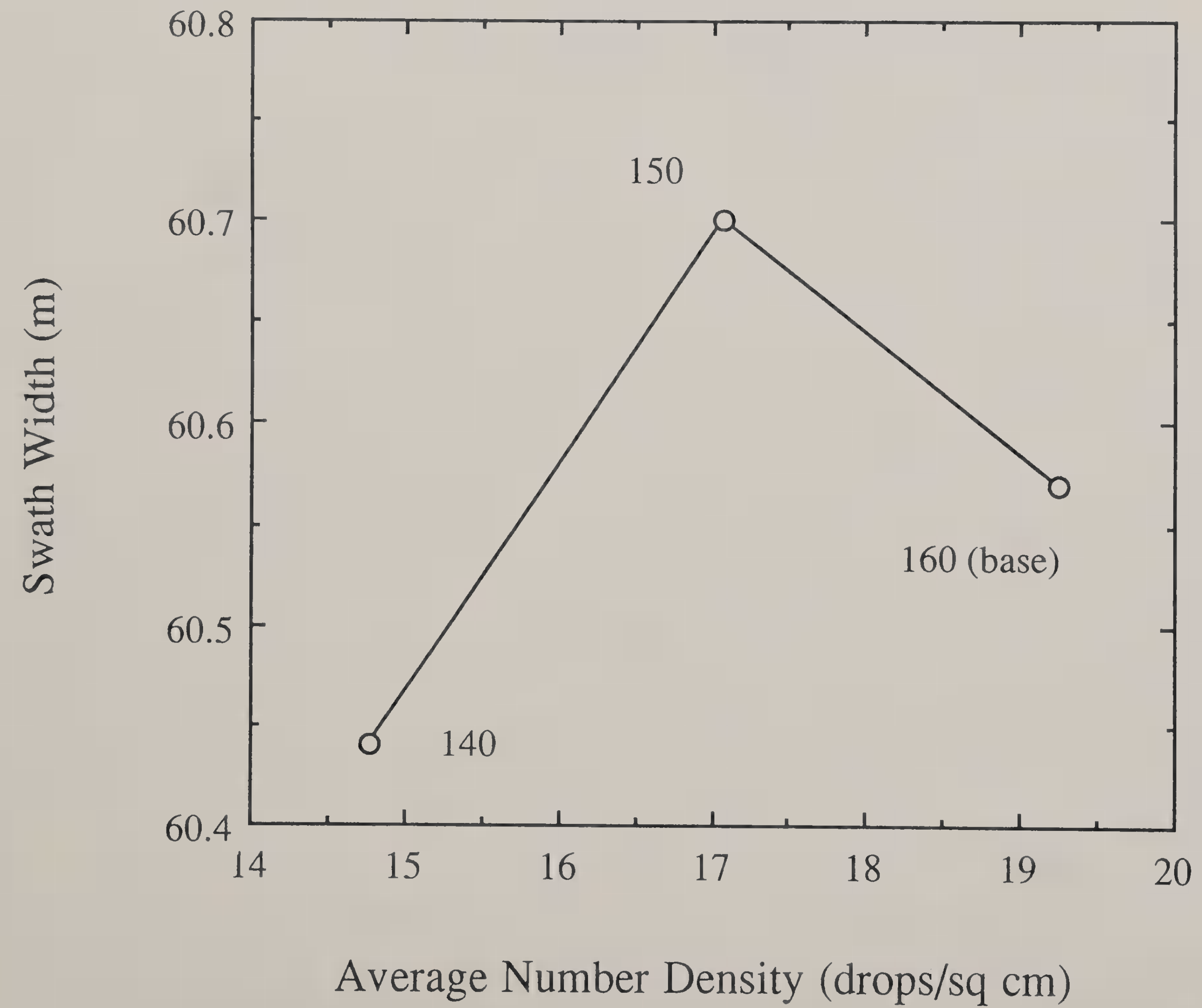


Figure 7. Sensitivity of the average (overlapped) number density and swath width to changes in air speed (in miles per hour as indicated).

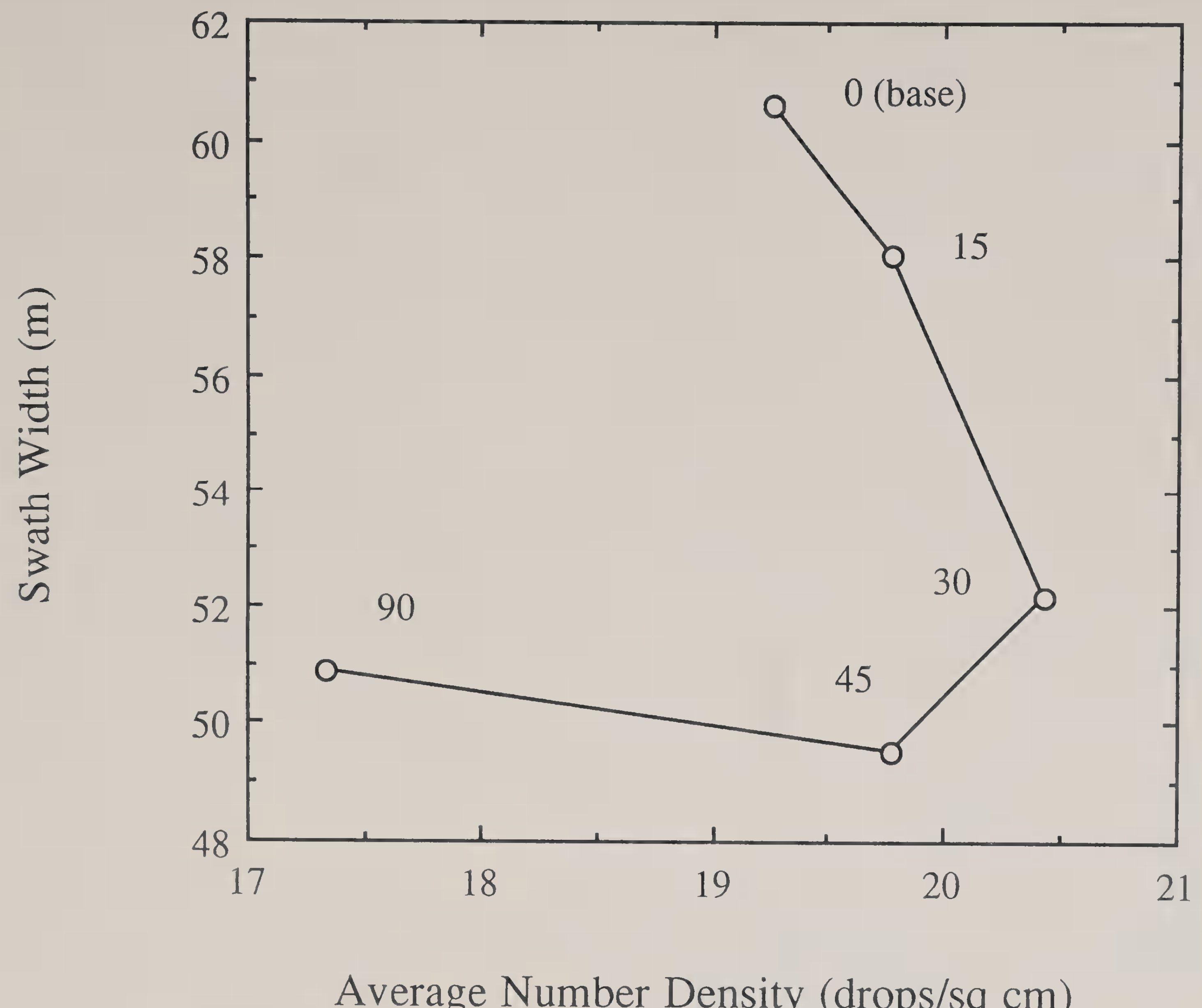


Figure 8. Sensitivity of the average (overlapped) number density and swath width to changes in wind direction (in degrees relative to the flight line as indicated).

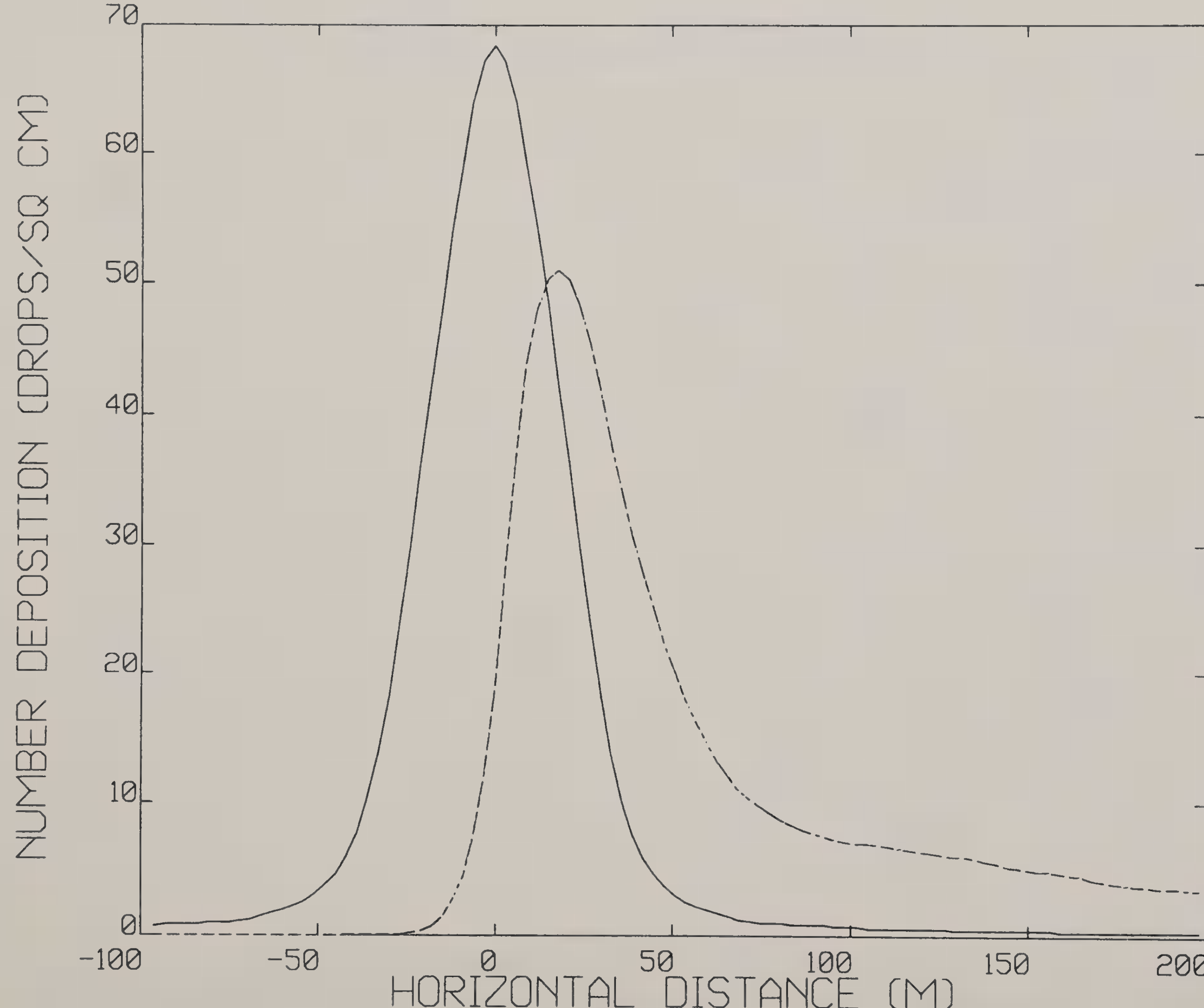


Figure 9. Comparison of in-wind (solid) with crosswind (dashed) number density deposition patterns.

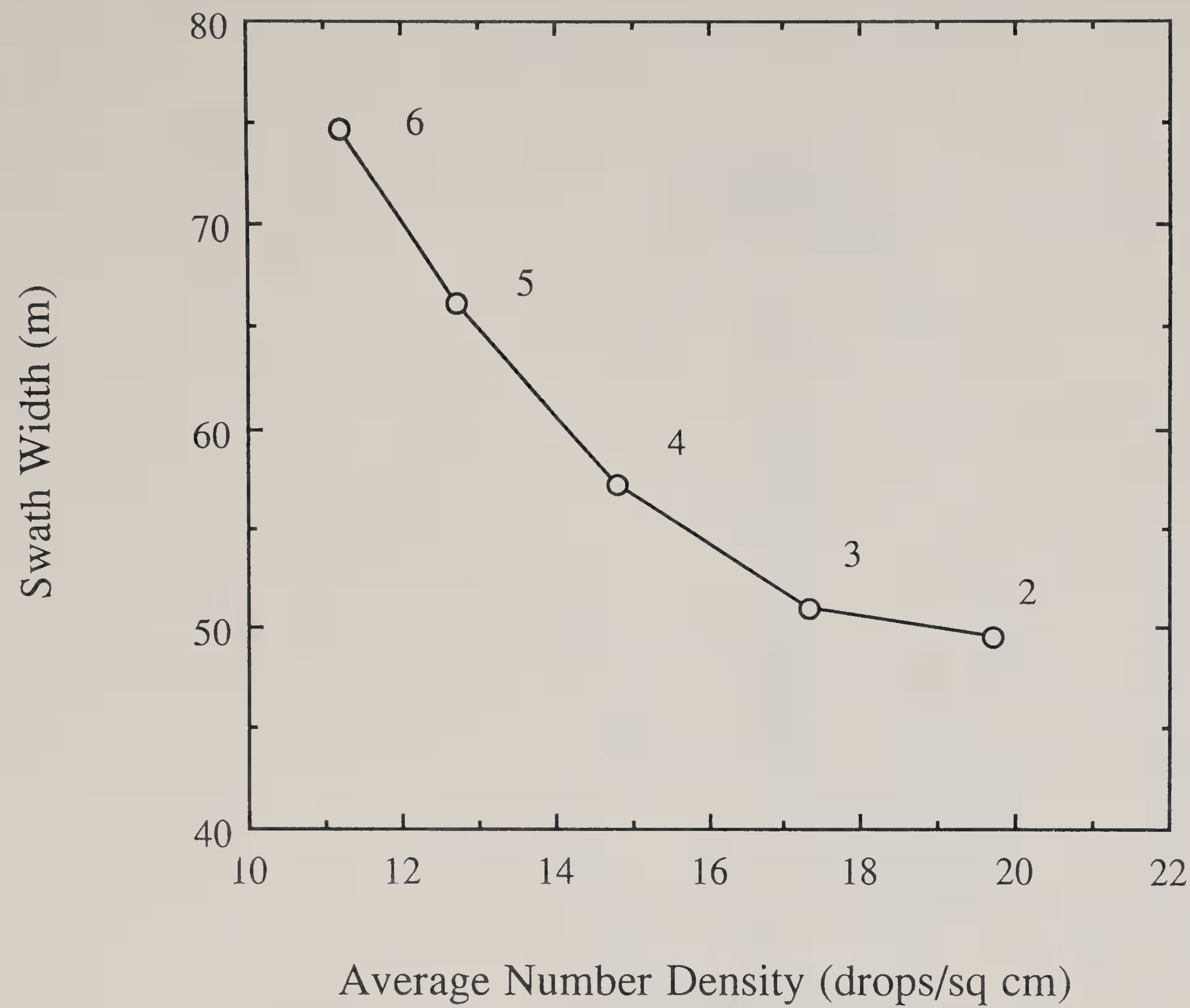


Figure 10. Sensitivity of the average (overlapped) number density and swath width to changes in wind speed with a 90 deg crosswind (in miles per hour as indicated).

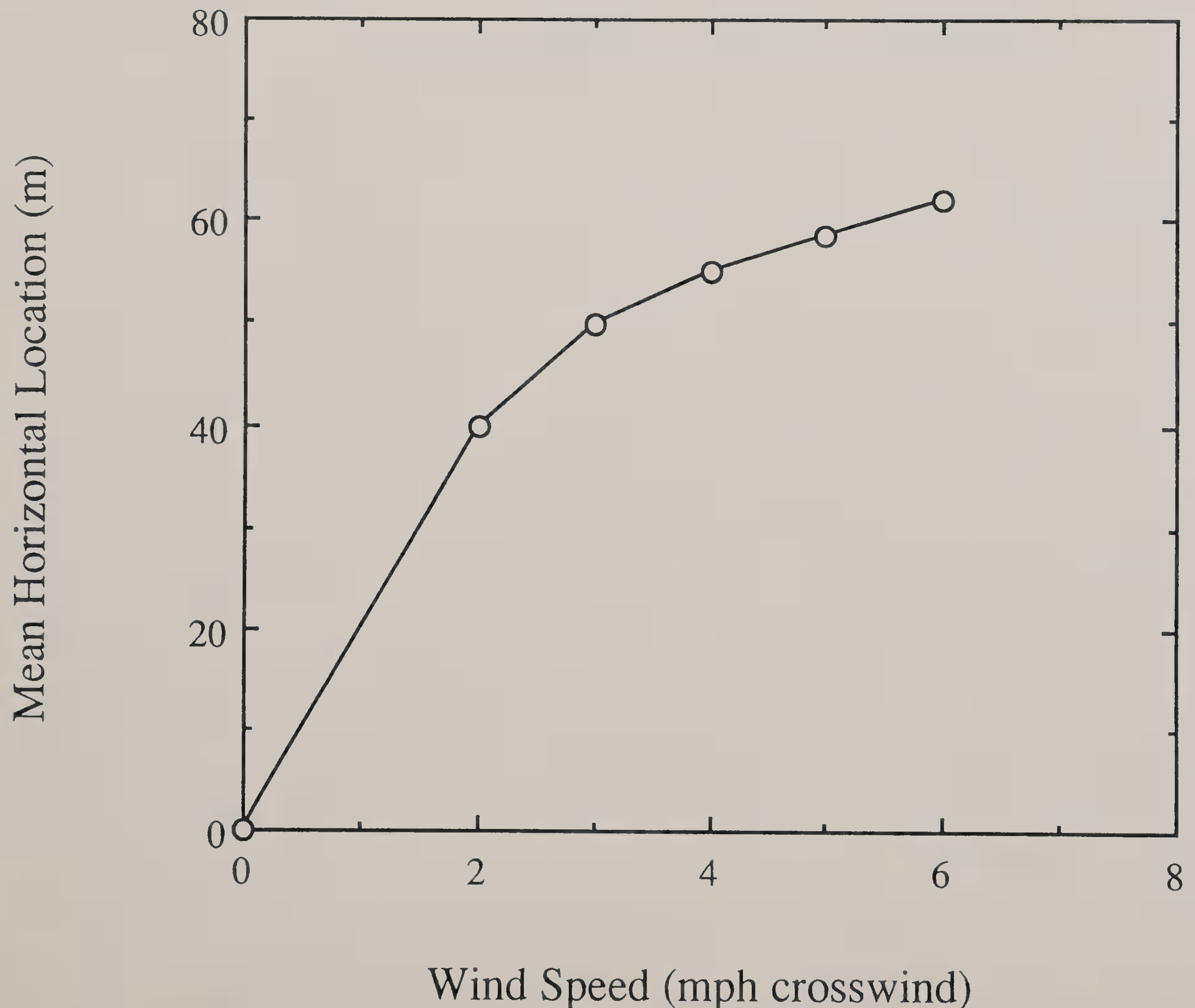


Figure 11. Sensitivity of the mean horizontal position of the ground deposition pattern to changes in crosswind.

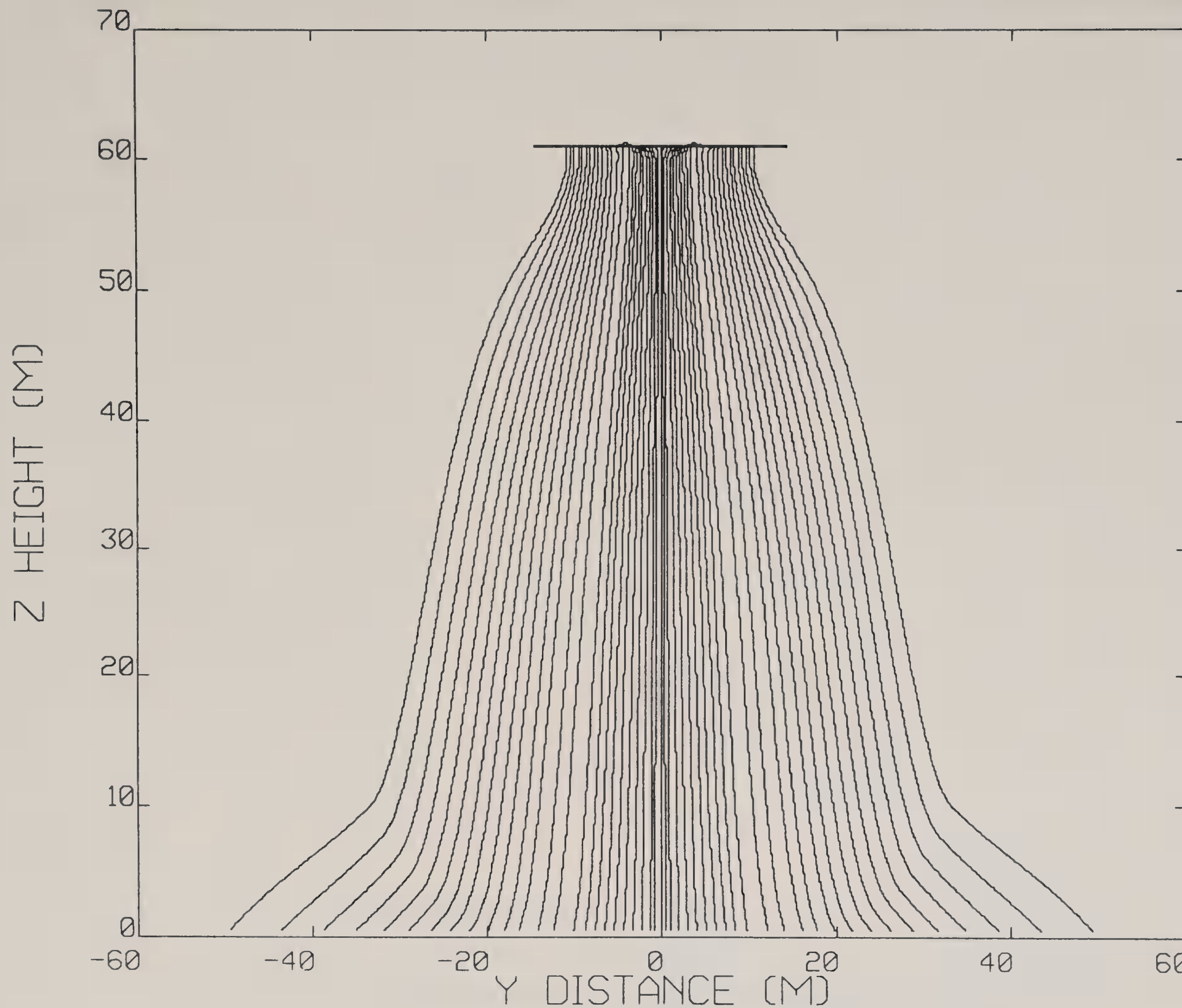


Figure 12. Typical trajectory patterns from 8020 flat fan nozzles on the DC-3.

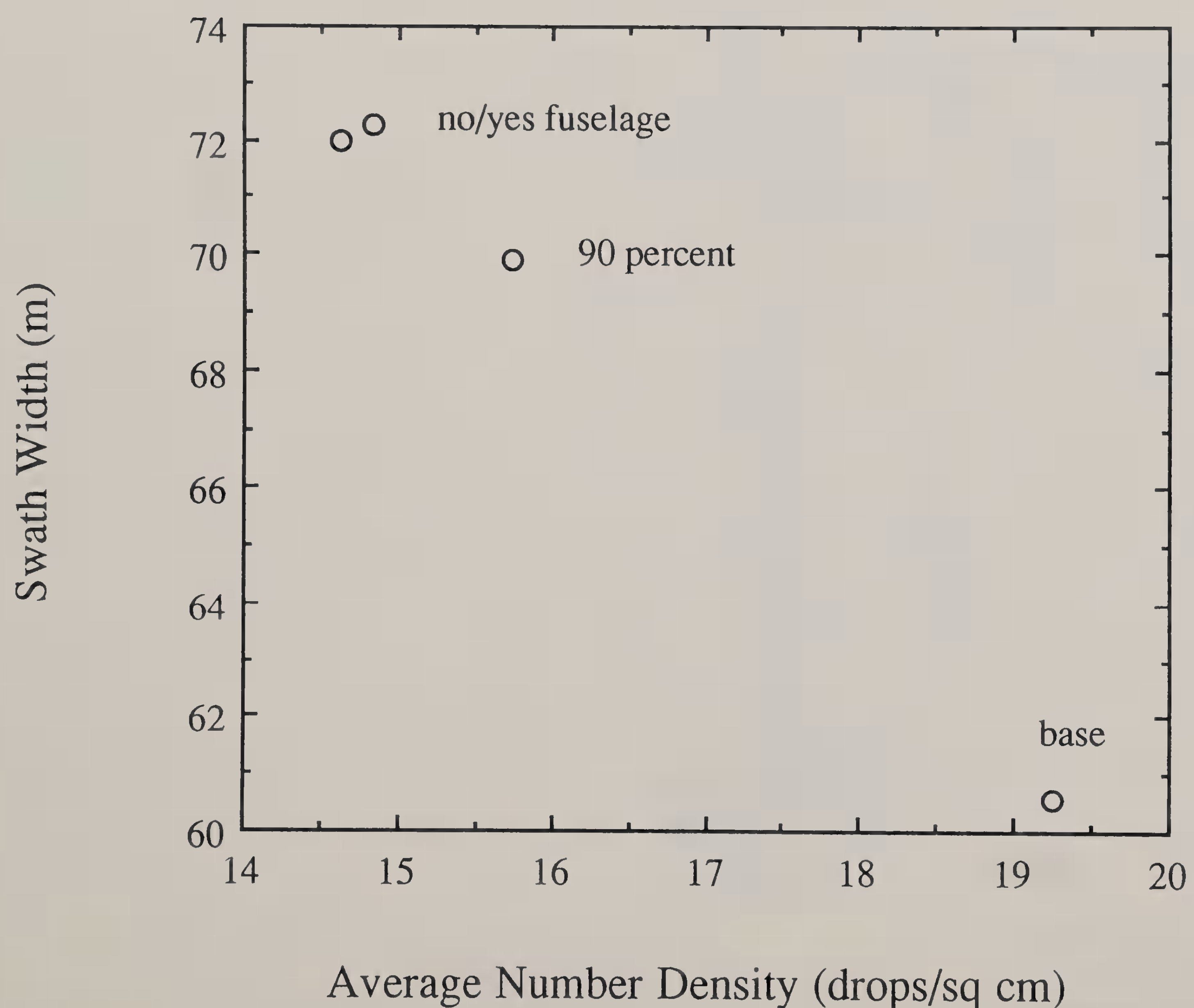


Figure 13. Sensitivity of the average (overlapped) number density and swath width to changes in nozzle distribution (as indicated).

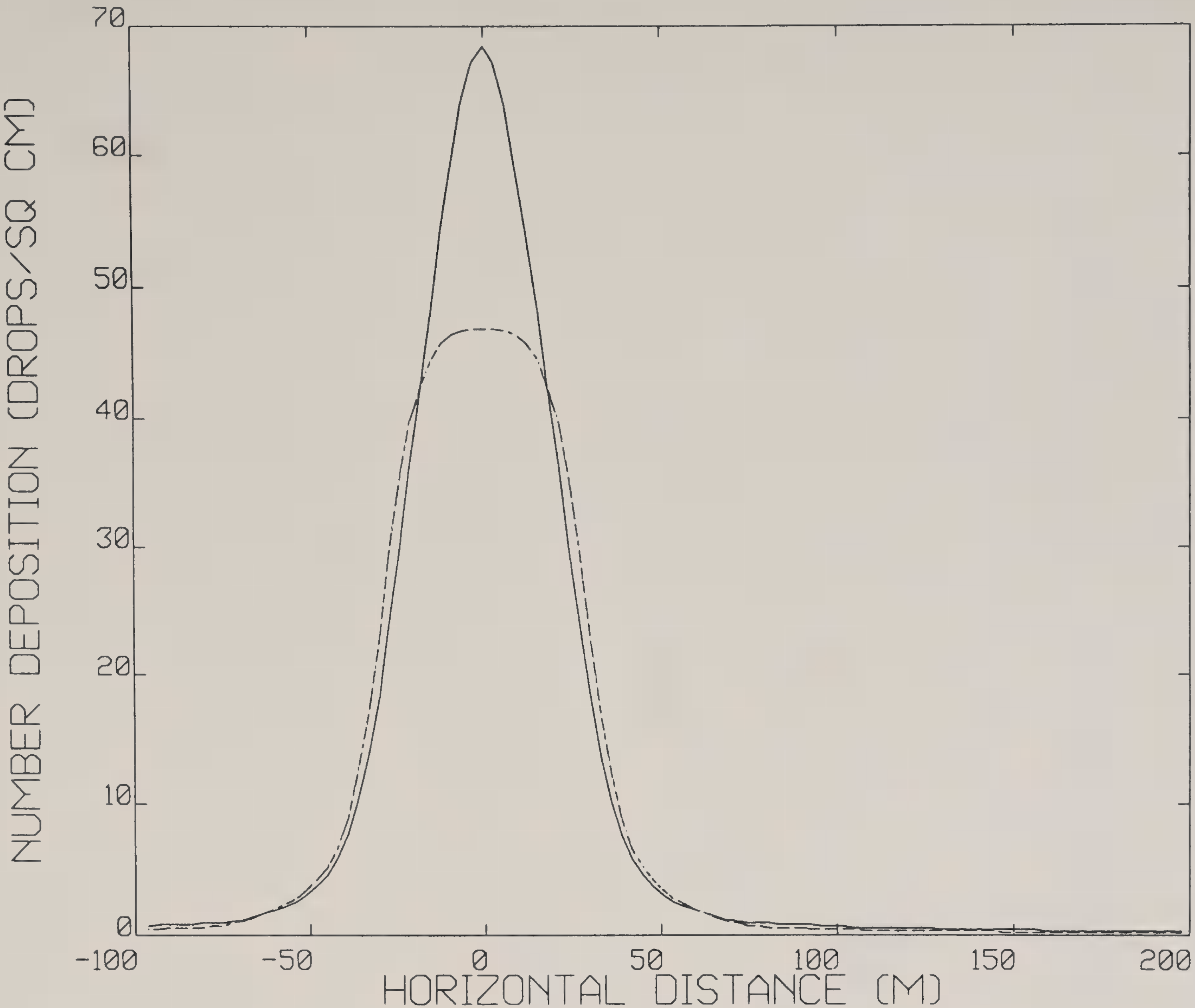


Figure 14a. Comparison of ground deposition pattern (number density) for the base case (solid) and nozzle repositioning toward the ends of the boom (dashed).

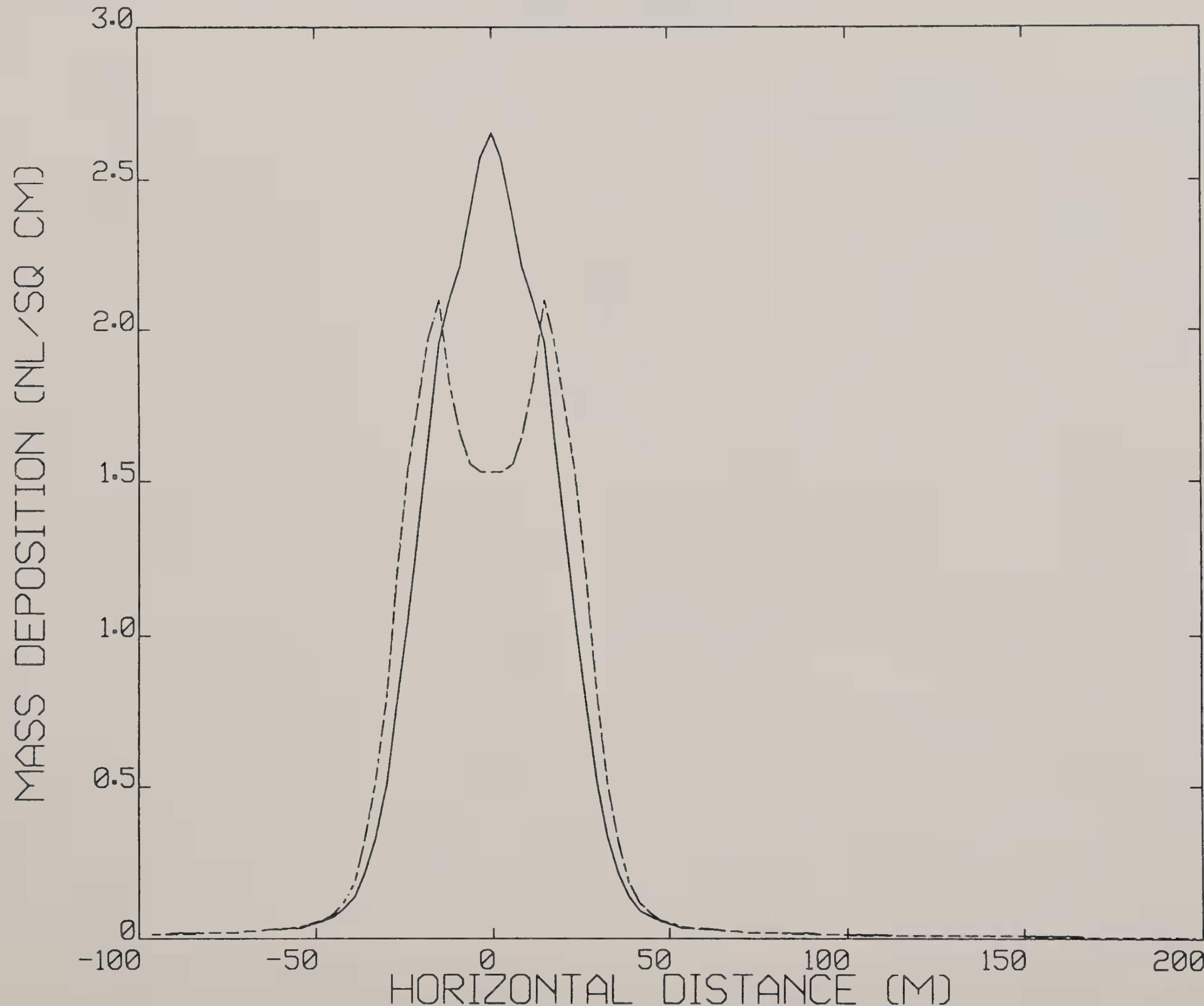


Figure 14b. Comparison of ground deposition pattern (mass) for the base case (solid) and nozzle repositioning toward the ends of the boom (dashed).

5. REFERENCES

1. M. E. Teske 1990: "AGDISP User Manual Mod 6.0," Continuum Dynamics, Inc. Technical Note No. 90-16.

2. M. E. Teske, D. B. Twardus and R. B. Ekblad 1990: "Swath Width Evaluation," USDA Forest Service Technology and Development Program Report No. 9034-2807-MTDC.

3. P. J. Skyler and J. W. Barry 1990: "Compendium of Drop Size Spectra Compiled from Wind Tunnel Tests," USDA Forest Service Forest Pest Management Report No. FPM-90-9.

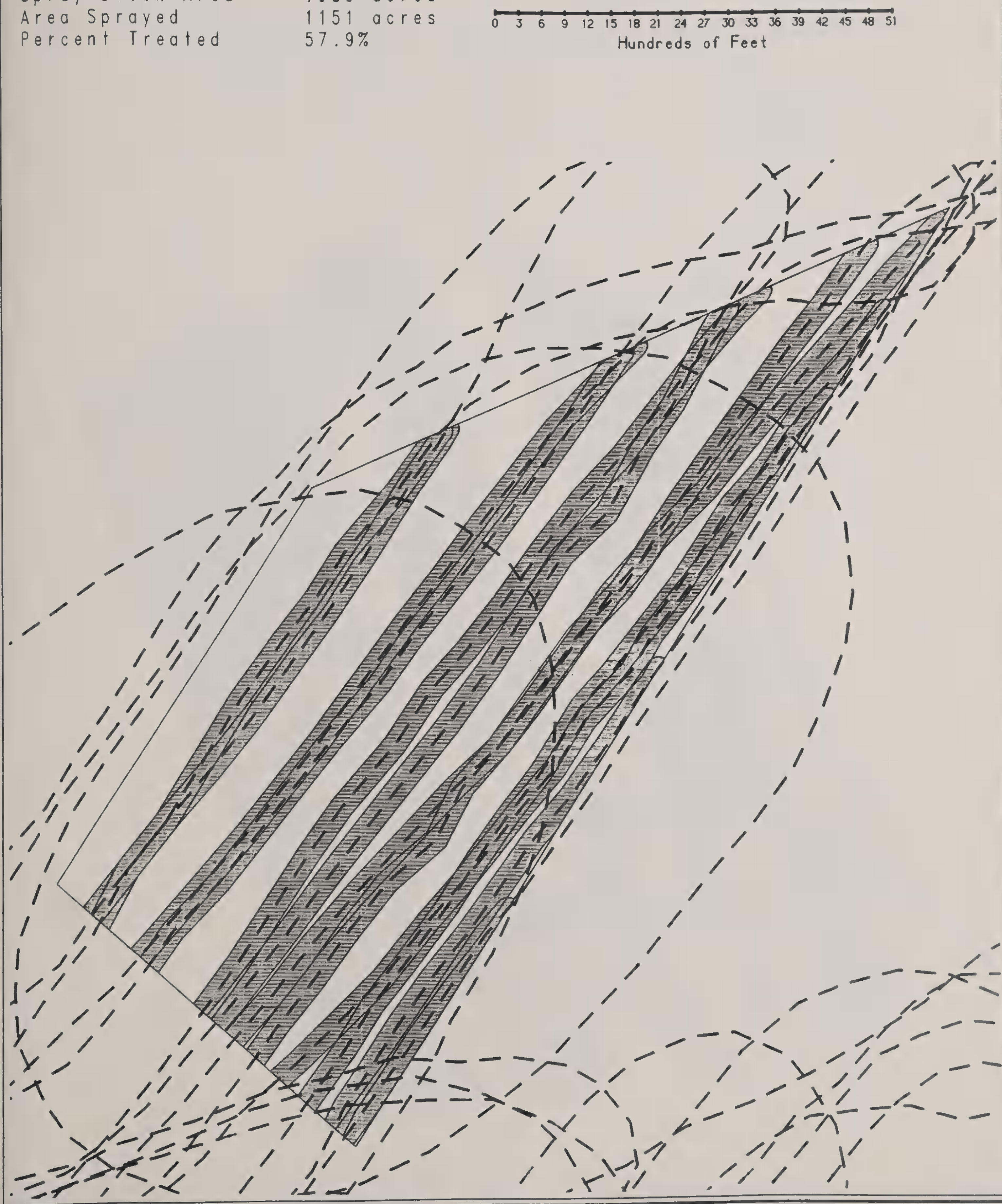
4. M. E. Teske 1990: "DROPSIZE User Manual," Continuum Dynamics, Inc. Technical Note No. 90-10.

Appendix B

Flight Paths and Simulated Swaths for 15 treatment blocks used in evaluating insecticide coverage.

Flight line for Block CUL51B.A
300 Foot Swath Width

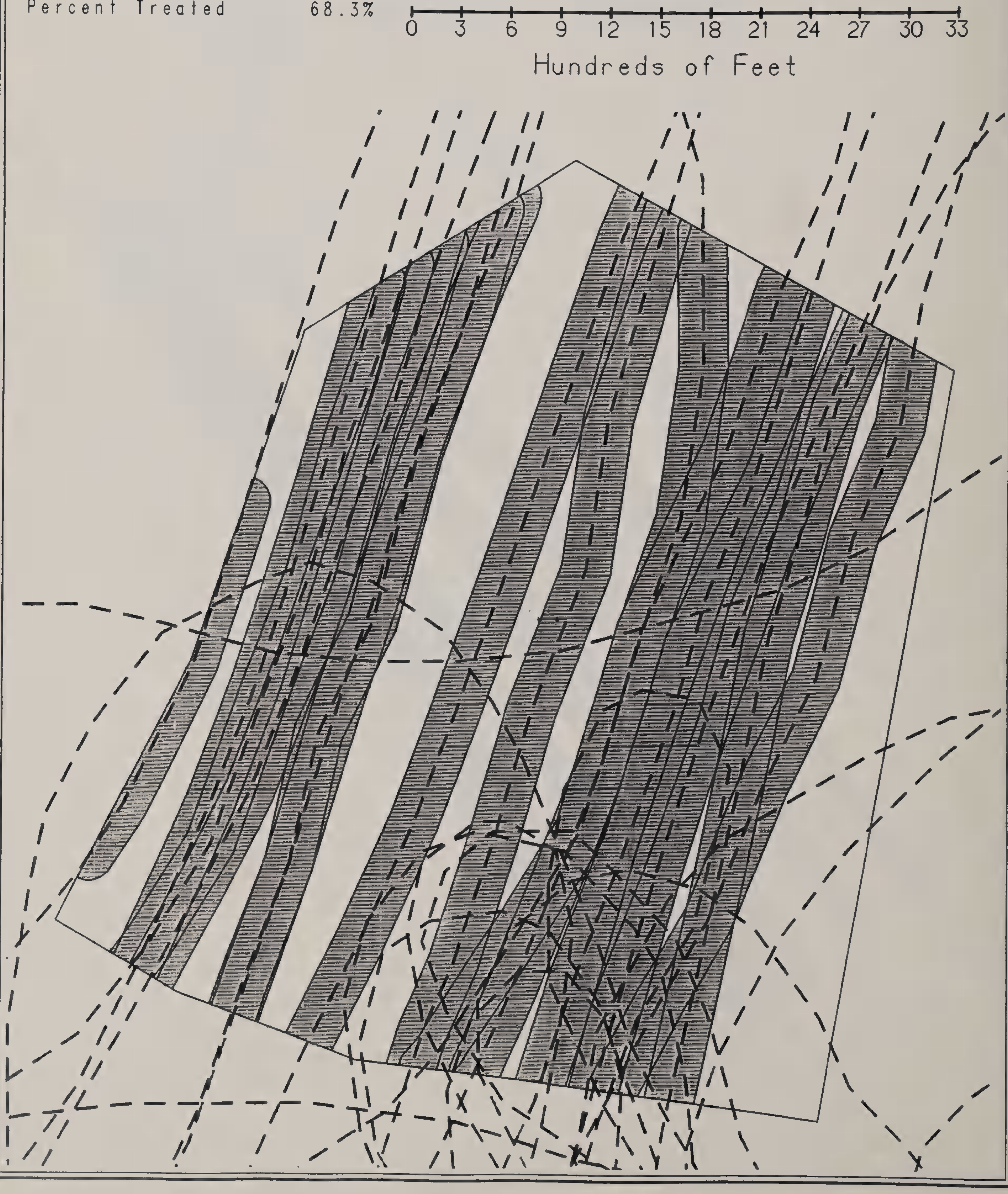
Spray Block Area 1989 acres
Area Sprayed 1151 acres
Percent Treated 57.9%



Flight line for Block PRWM52.A

300 Foot Swath Width

Spray Block Area 483 acres
Area Sprayed 330 acres
Percent Treated 68.3%

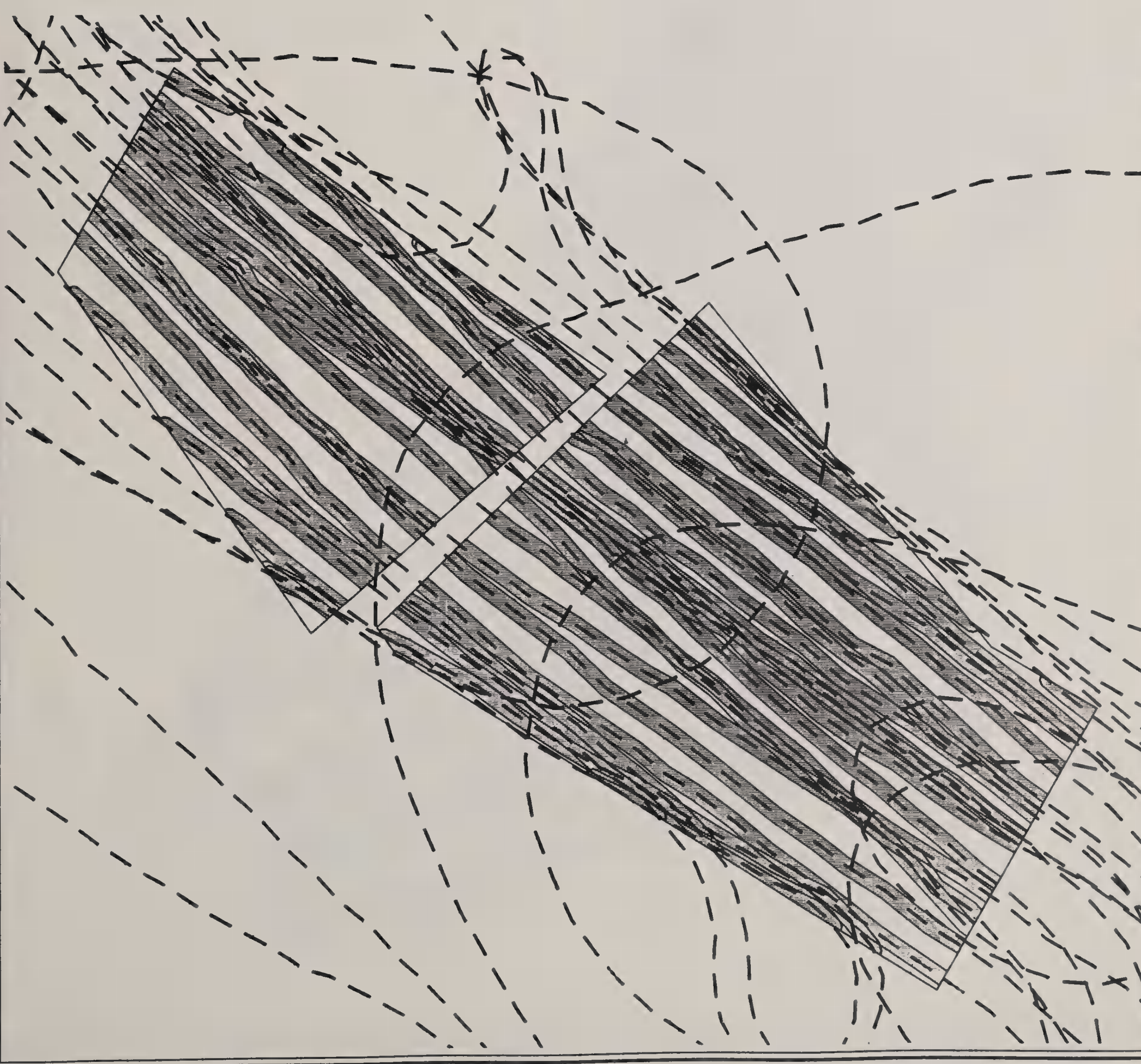


Flight line for Block CUL430.A

300 Foot Swath Width

Spray Block Area 2953 acres
Area Sprayed 1890 acres
Percent Treated 64.0%

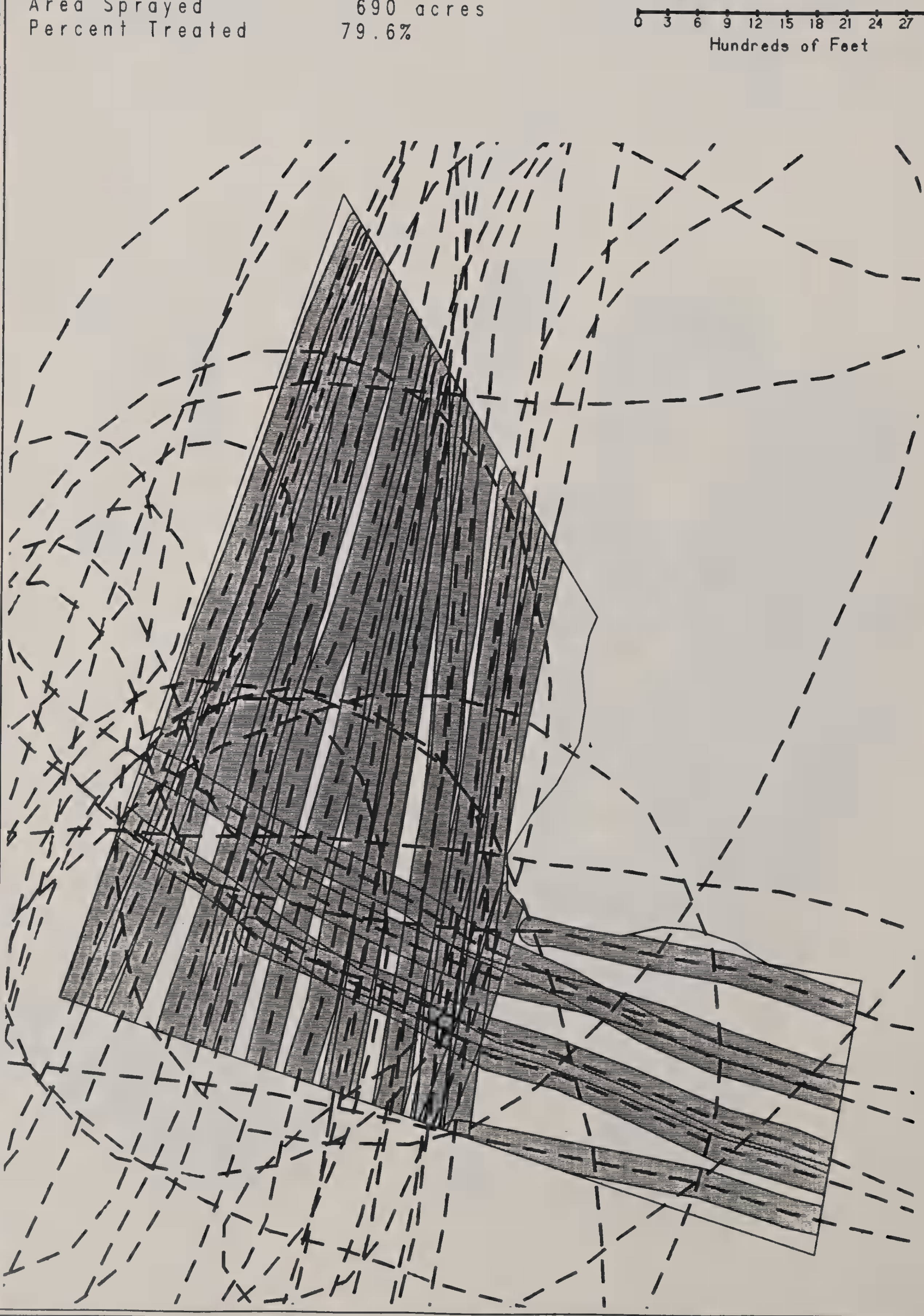
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51
Hundreds of Feet



Flight line for Block CUL51.B

300 Foot Swath Width

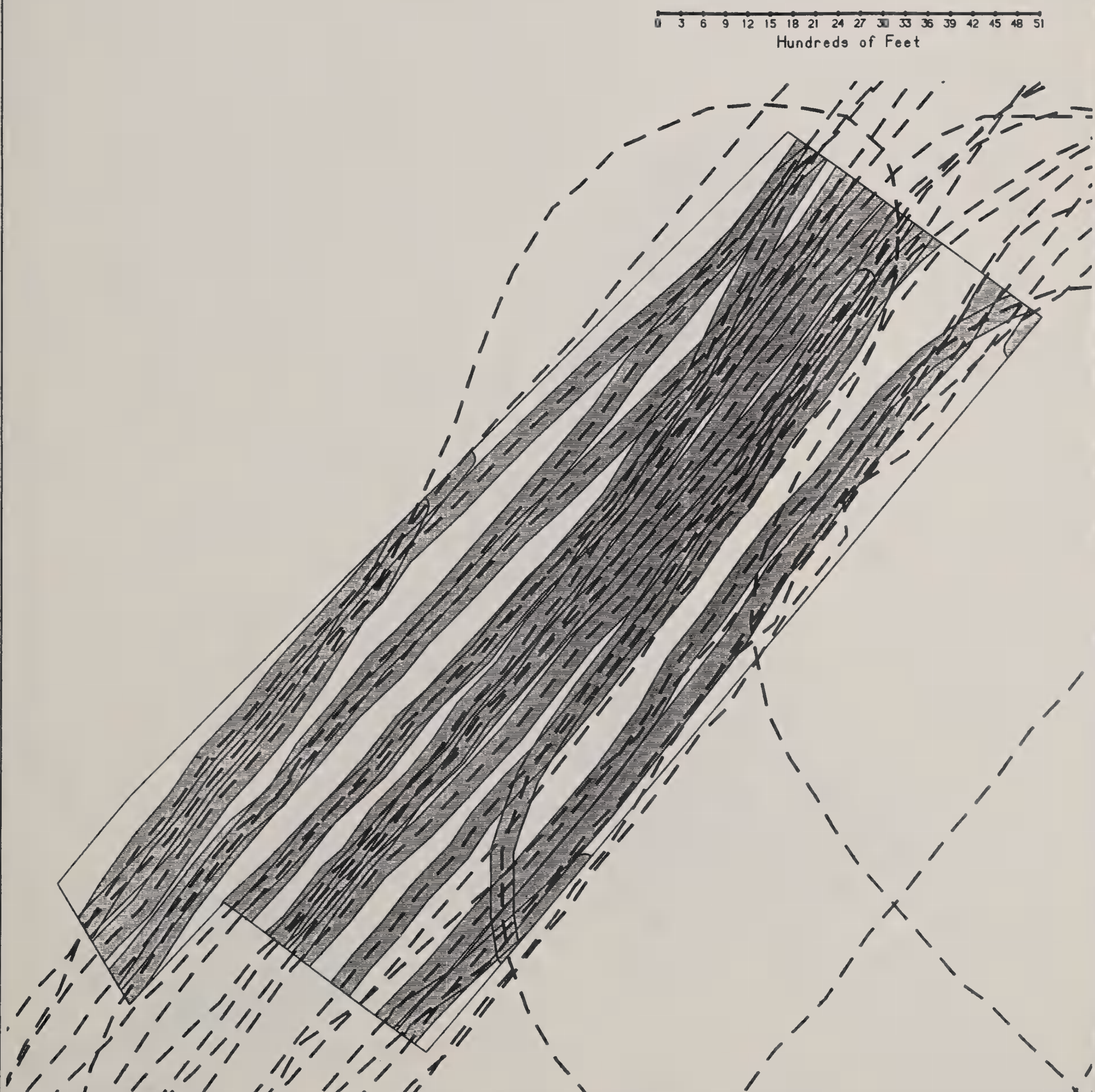
Spray Block Area 867 acres
Area Sprayed 690 acres
Percent Treated 79.6%



Flight line for Block FR53.A

300 Foot Swathwidth

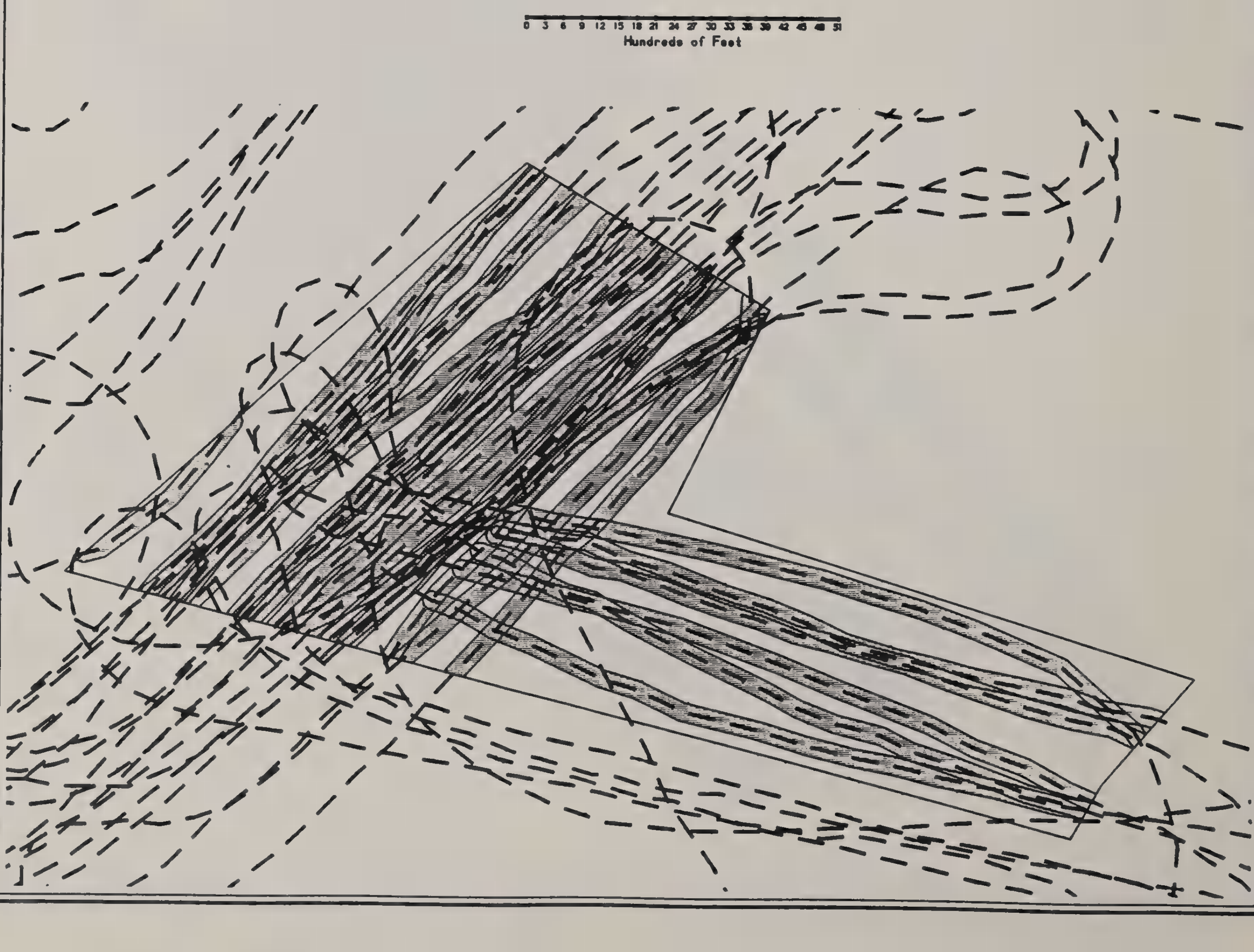
Spray Block Area	1441 acres
Area Sprayed	951 acres
Percent Treated	66.0%



Flight line for Block FR53.C

300 Foot Swathwidth

Spray Block Area	1855 acres
Area Sprayed	1149 acres
Percent Treated	61.9%

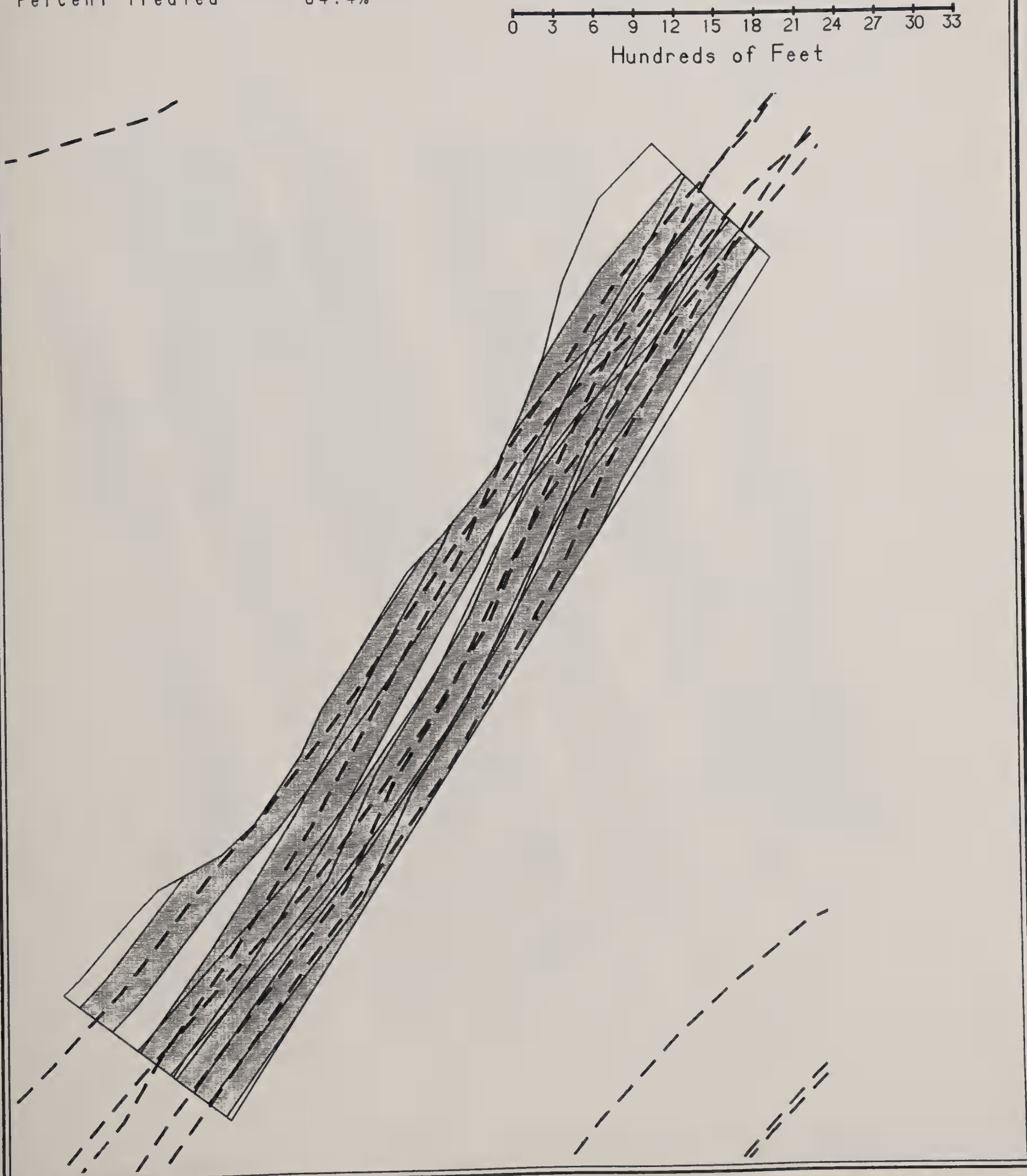


Plotfile: FR53.C.PLT

Flight line for Block FR53.B

300 Foot Swathwidth

Spray Block Area 199 acres
Area Sprayed 168 acres
Percent Treated 84.4%

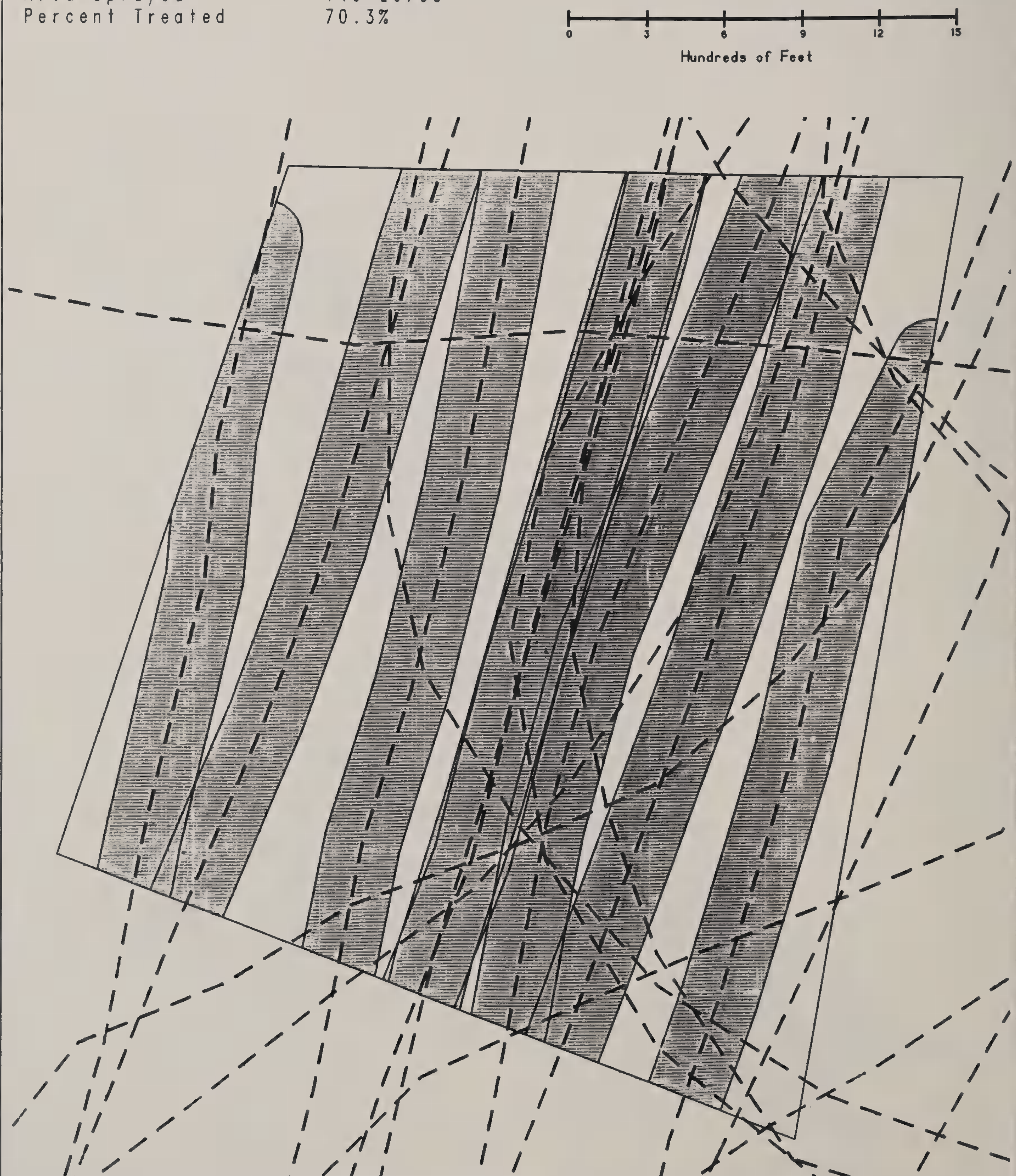


Plotfile: FR53.B.PLT

Flight line for Block CUL51.A

300 Foot Swathwidth

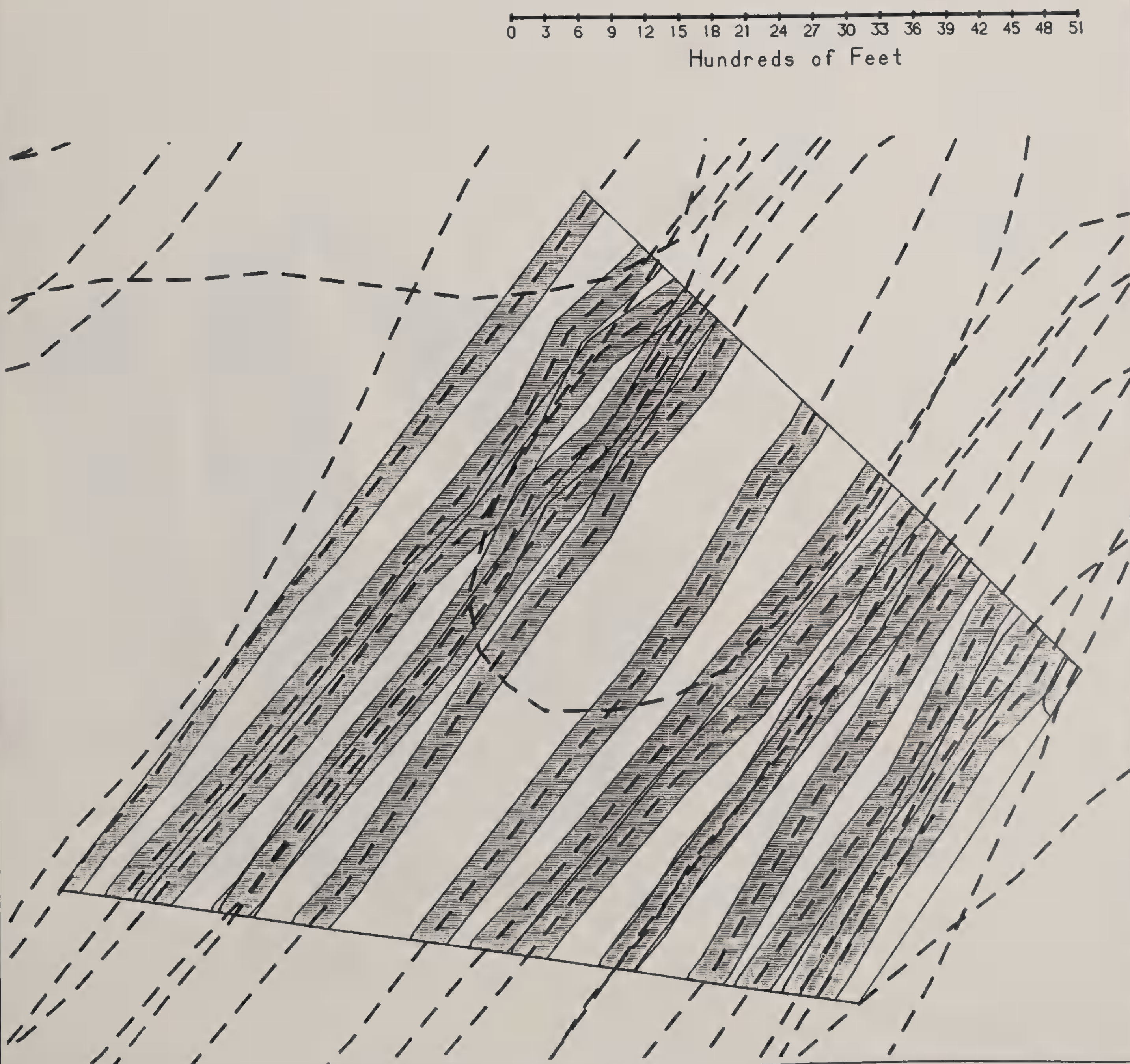
Spray Block Area	212 acres
Area Sprayed	149 acres
Percent Treated	70.3%



Plotfile: CUL51.A.PLT

Flight line for Block CUL51B.B
300 Foot Swathwidth

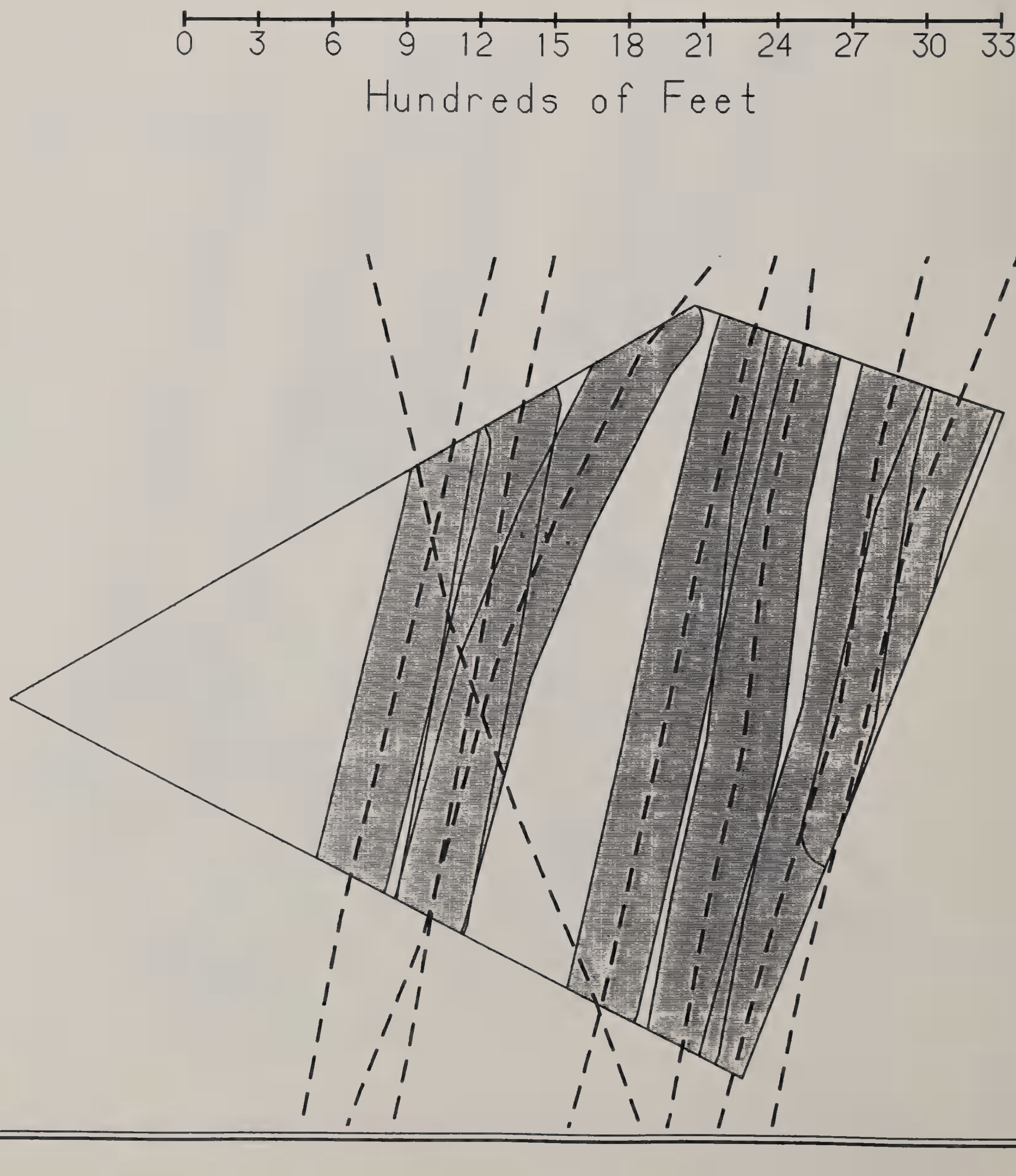
Spray Block Area	824 acres
Area Sprayed	499 acres
Percent Treated	60.6%



Plotfile: CUL51B.B.PLT

Flight line for Block CUL51.C
300 Foot Swathwidth

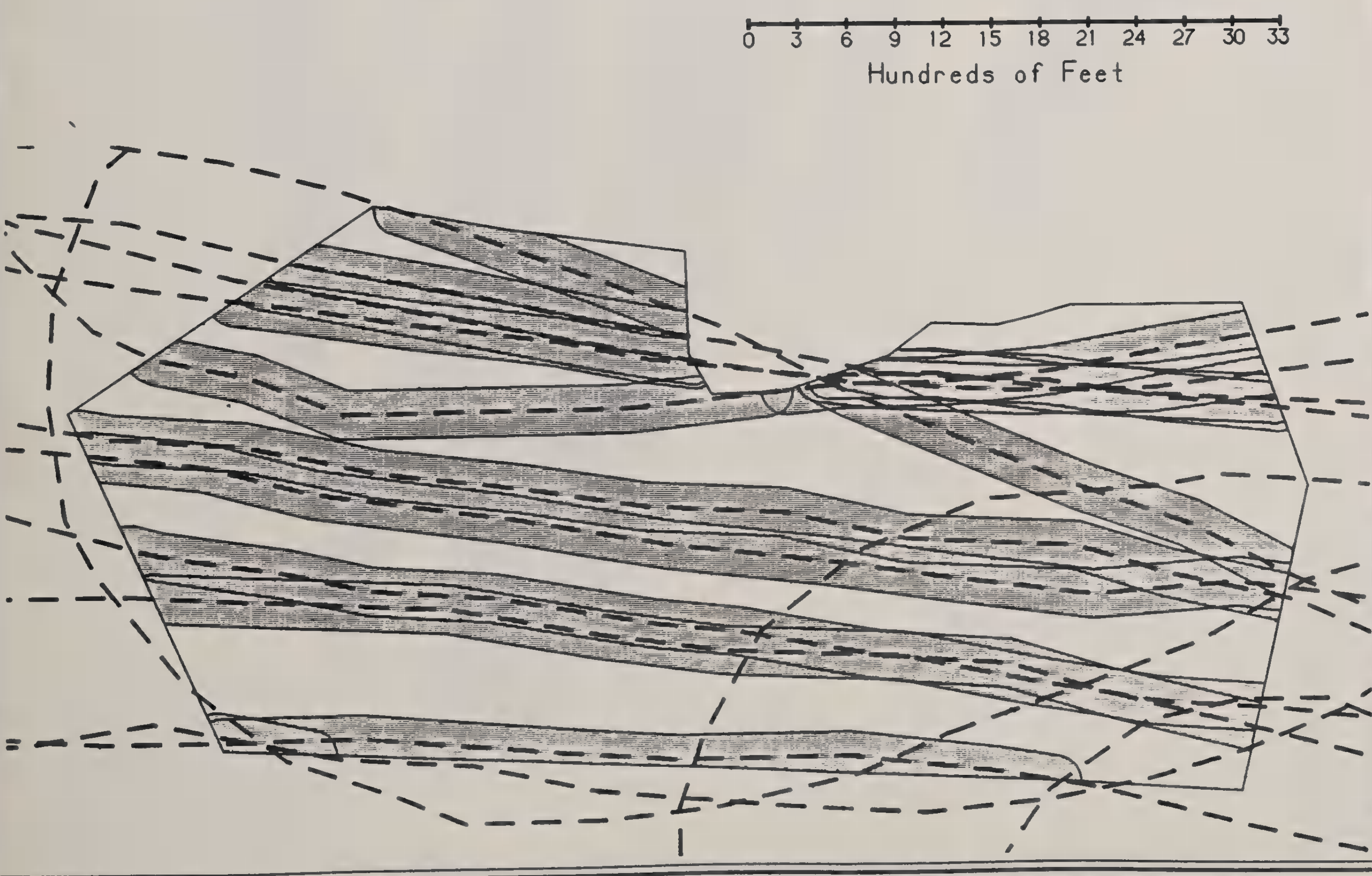
Spray Block Area 147 acres
Area Sprayed 96 acres
Percent Treated 65.3%



Plotfile: CUL51.C.PLT

Flight line for Block PRWM53.C
300 Foot Swathwidth

Spray Block Area	471 acres
Area Sprayed	290 acres
Percent Treated	61.6%



Plotfile: PRWM53.C.PLT

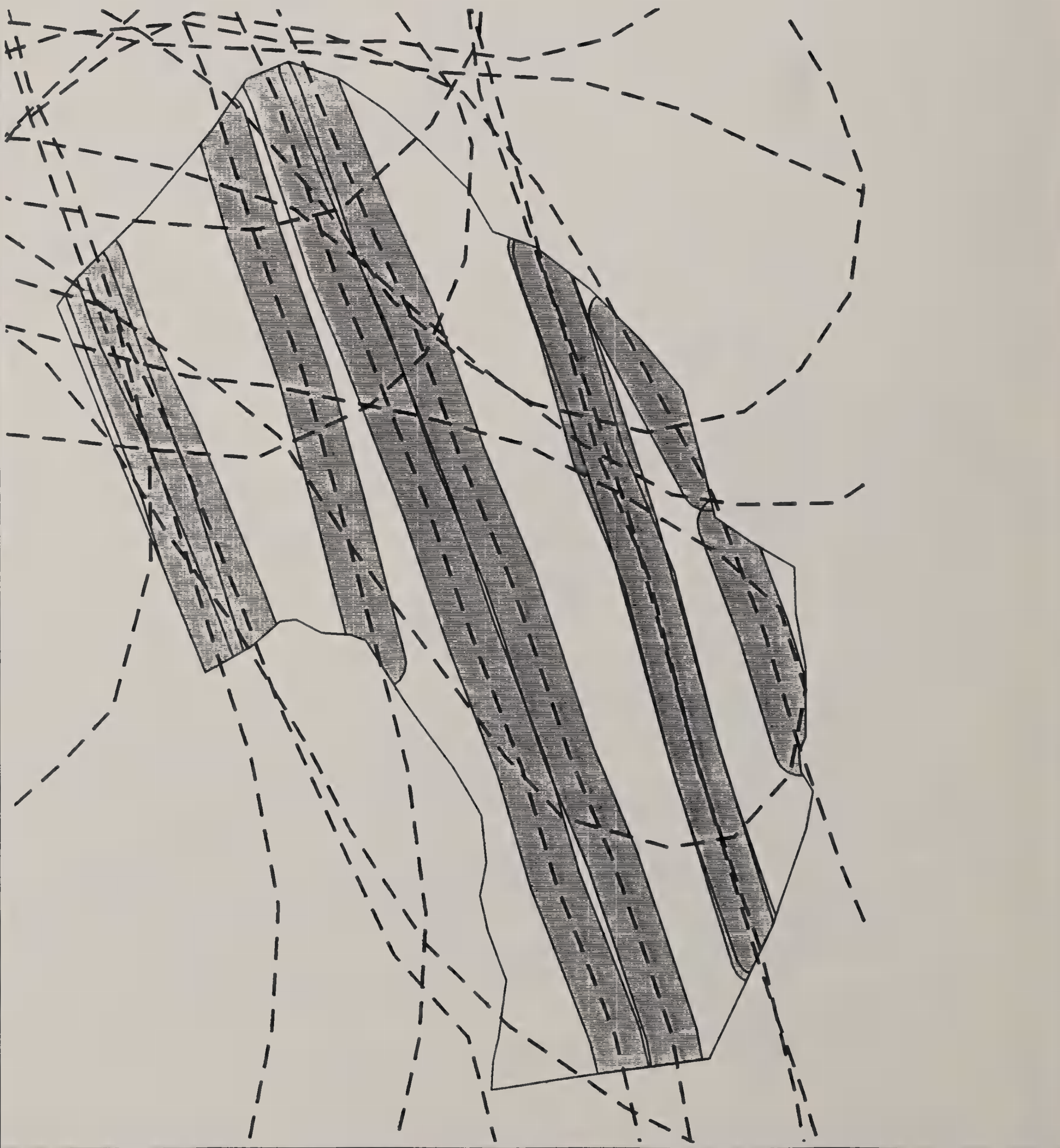
Flight line for Block PRWM53.D

300 Foot Swathwidth

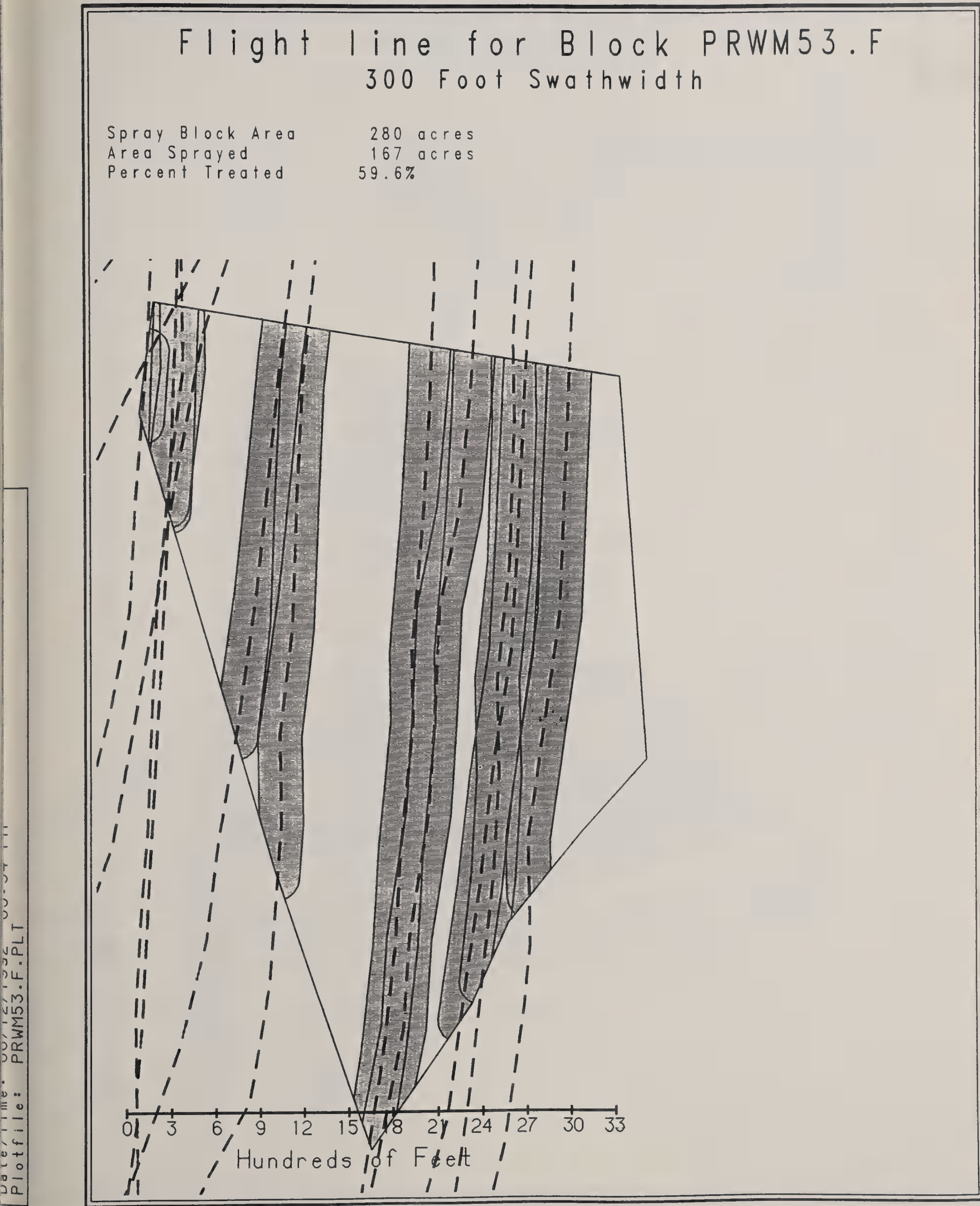
Spray Block Area	318 acres
Area Sprayed	179 acres
Percent Treated	56.3%

0 3 6 9 12 15 18 21 24 27 30 33

Hundreds of Feet



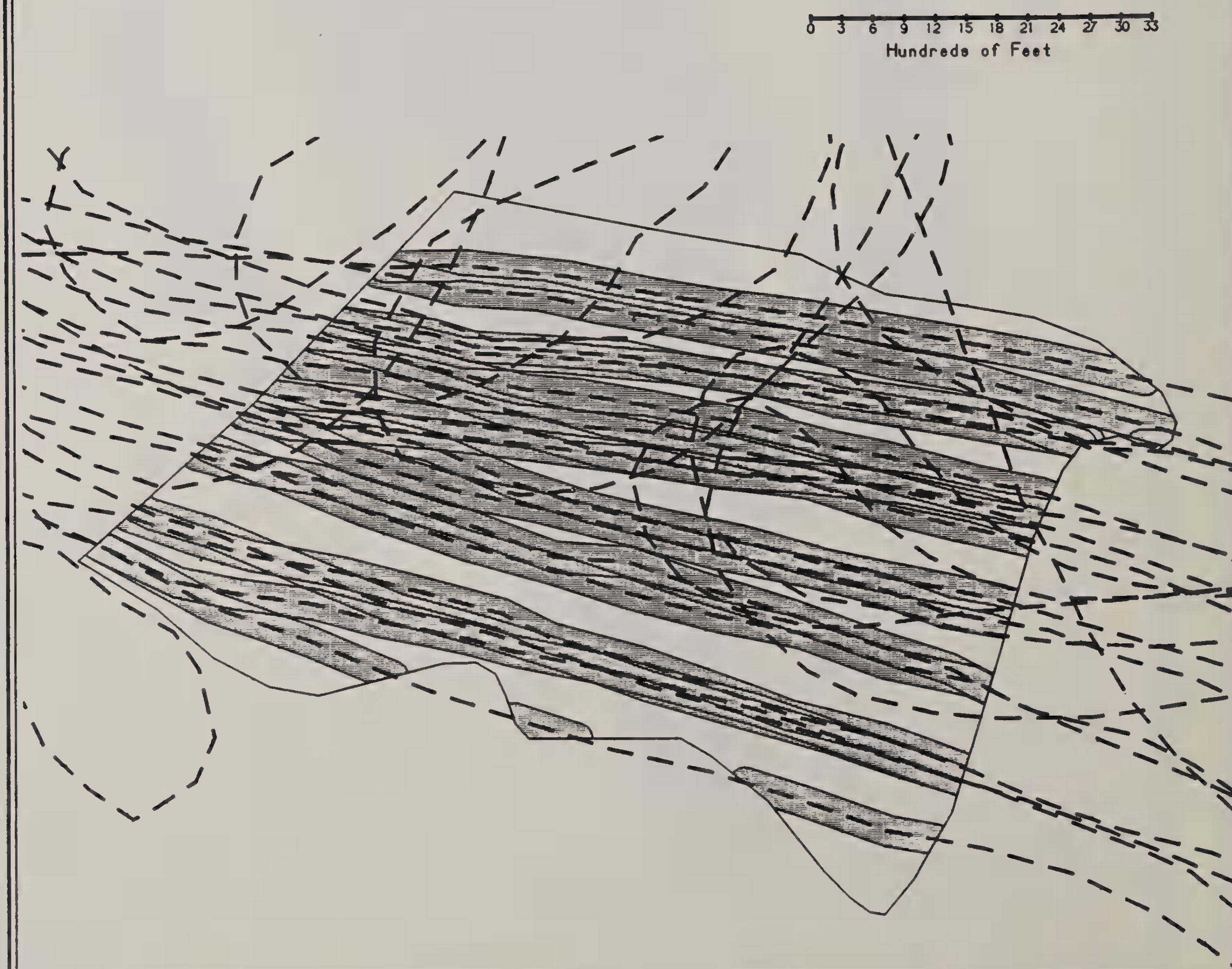
Plotfile: PRWM53.D.PLT


Flight line for Block PRWM53.F
300 Foot Swathwidth
Spray Block Area 280 acres
Area Sprayed 167 acres
Percent Treated 59.6%
0 3 6 9 12 15 18 21 24 27 30 33
Hundreds of Feet
Plotfile: PRWM53.F.PLT

Flight line for Block PRWM52.C

300 Foot Swathwidth

Spray Block Area	899 acres
Area Sprayed	598 acres
Percent Treated	66.5%



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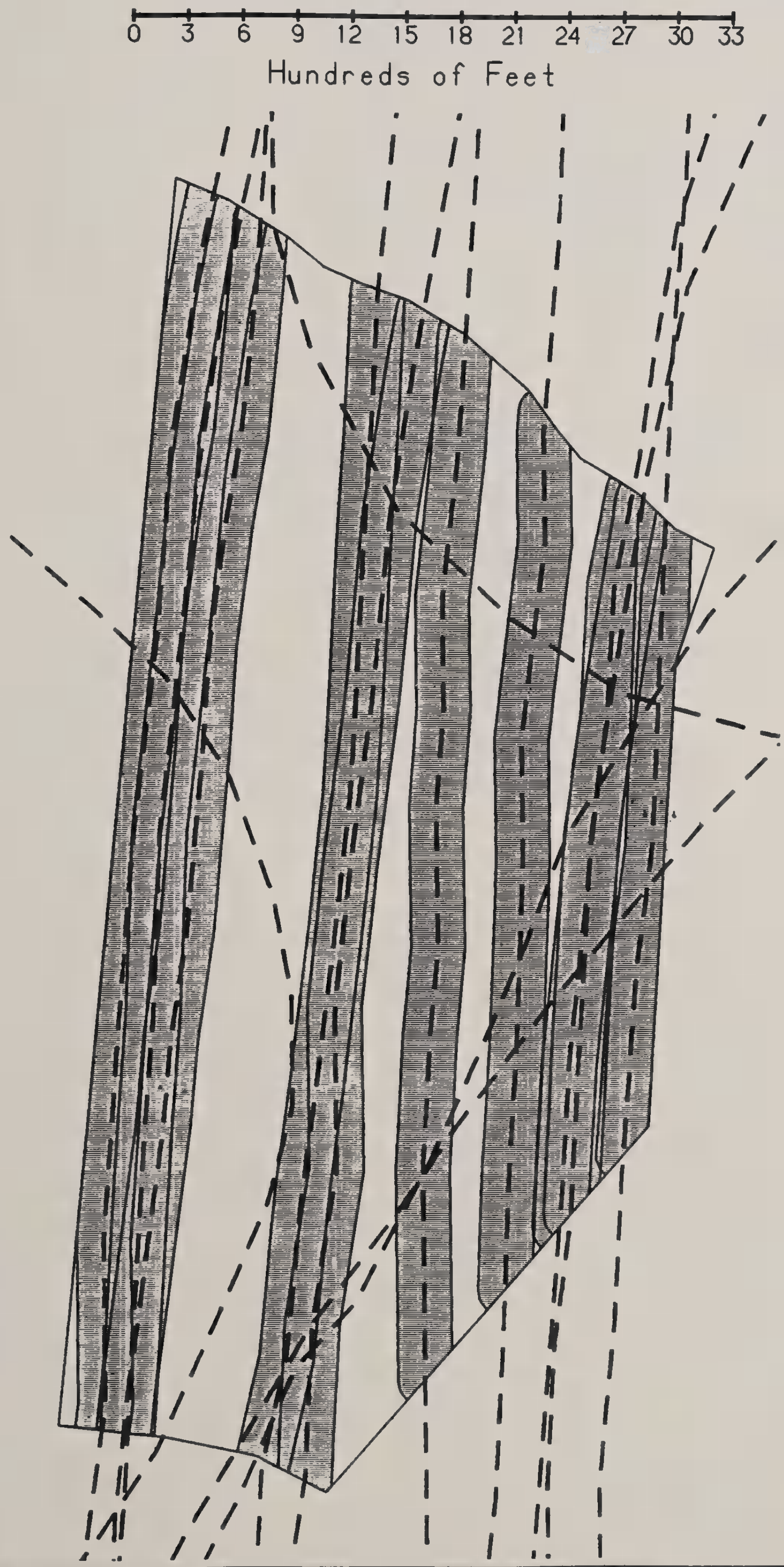
Plotfile: PRWM52.C.PLT

Flight line for Block PRWM53.E

300 Foot Swathwidth

Spray Block Area	403 acres
Area Sprayed	275 acres
Percent Treated	68.2%



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Appendix C

An Interpretation of the DC-3 Swath Width Field Trials

Introduction

Aerial application is used by the USDA Forest Service to control harmful insects and protect trees. Over the years spraying for gypsy moth (*Lymantria dispar L.*) has become more and more extensive, especially in the Northeast. One measure of the effectiveness of an aircraft at depositing spray material is its swath width. Swath width is that portion of the canopy or ground deposition profile considered usable to achieve the objectives of spraying. Swath width for a particular aircraft is dependent upon spray drop size distribution, nozzle type and location, aircraft flight speed and release height, the formulation being sprayed, and ambient wind and atmospheric conditions. Field work in the early to mid 1960s by the Animal Plant Health Inspection Service APHIS established swath width guidelines still in use today.

The simulation of the behavior of aerially released sprays has been programmed into the AGDISP (AGricultural DISPersal) model (Teske 1991a). AGDISP is based on a Lagrangian approach to the solution of the equations of motion, tracking the released spray from specified nozzle locations into the atmosphere. Similar sized droplets are combined into a spray drop size distribution to generate the spray droplet cloud, which in turn is tracked to and deposited onto the canopy or ground.

Swath width is evaluated in AGDISP by developing a prediction for lane separation. Lane separation is the operational distance between successive flight lines, and is determined by numerically overlapping adjacent flight lines to minimize deposition variation across the spray deposition profile. Deposition predictions from AGDISP for a single aircraft flight line are offset by lane separation and overlapped. The deposition variation is measured by computing the relative standard deviation, or coefficient of variation COV, of the resulting spray profile. Previous work (Quantick 1985) suggests that a value of COV equal to 0.3 provides an acceptable overlap criterion. Other approaches, such as requiring a minimum deposition level across the spray profile, may also be applied.

Recently, the APHIS guidelines were compared against swath width predictions made by AGDISP (Teske, Twardus and Ekblad 1990). For the most part the AGDISP predictions showed somewhat larger values than the APHIS guidelines. The most notable exception was the comparison with the DC-3, where the APHIS guidelines recommend a swath width of 300 feet while the AGDISP predictions suggest a swath width of 201 feet.

Because the DC-3 is an aircraft used extensively in spraying for gypsy moth, this swath width disparity required further examination. Therefore, as a prelude to field trials of the DC-3, a sensitivity study was first undertaken (Teske 1991b). This study concluded that inwind application, and repositioning nozzles outward along the spray boom (even out to 90 percent of the wing semispan) are the only ways to improve the DC-3 swath width. As it is, these improvements will increase the swath width to 237 feet, still well below the APHIS guidelines.

Subsequently, field trials were developed (Ghent 1991) and conducted (Twardus and Ghent 1992). One of the objectives of the trials was to confirm the AGDISP model predictions, thereby supporting the earlier predictions of swath width and the sensitivity study results.

Field Trials

The DC-3 field trials reproduced typical gypsy moth spray operation parameters. The aircraft was flown over three parallel card lines, each 500 feet long, spaced 100 feet apart and oriented perpendicular to the aircraft flight path. These card lines were originally laid perpendicular to the measured wind direction, so that the aircraft would fly inwind and hence enhance its swath width as suggested by the sensitivity study. The deposition data on the three card lines were averaged to present a single card line for swath width analysis.

In addition, two card lines were oriented parallel to the aircraft flight path, 50 feet on either side of the centerline of the aircraft, in an attempt to recover flight line variation data.

Five different spray boom scenarios were considered: (1) an initial configuration where nozzles were distributed across 75 percent of the wing span; (2) an extended configuration where nozzles were removed from the center section of the spray boom and repositioned out to 90 percent of the wing semispan; and three dissection configurations where (3) nozzles were active only in the center section of the spray boom; (4) nozzles were active only in the midsection of the spray boom; and (5) nozzles were active only in the boom ends of the spray boom.

Results and interpretation are discussed in Twardus and Ghent (1992).

Swath Width

The sensitivity study can be used to infer the swath widths determined in the initial and extended configurations, by correcting previous predictions for changes in relative humidity, release height, air speed and wind direction, as well as crosswind speed and nozzle locations extended to 90 percent of wing semispan. Air speed did not show any significant variation in the sensitivity study, and temperature variation was not considered. The base case swath width was predicted by AGDISP to be 60.6 meters (199 feet). The slight difference from the original prediction of swath width of 201 feet is attributed to the slightly different base case assumptions in the two studies.

Modifications to the base case result are shown in Table 1, along with the swath widths determined by the field trials. Interpolation of the sensitivity study results has been made for changes in relative humidity, release height and nozzle locations (Figures 5, 6 and 13 of Teske 1991b respectively). Wind speed and direction changes must be corrected by examining the average measured wind speed and average wind direction, since the sensitivity study only looked at wind direction effects with a wind speed of 3 mph and wind speed effects in crosswind. The relevant wind speed is crosswind. An equivalent wind direction at 3 mph must be computed by equating the crosswind velocity components; for trial I1 this procedure yields

$$1.4 \sin 54 = 3.0 \sin \Theta = 1.13 \text{ mph}$$

to recover an equivalent wind direction angle of $\Theta = 22$ deg. This value of angle is then used to recover the wind direction effect from the sensitivity study (Figure 8 of Teske 1991b). Wind speed is corrected in the sensitivity study (Figure 10 of Teske 1991b) by correcting for crosswind (1.13 mph in trial I1) from a crosswind value of 0.0 mph (a swath width of approximately 49.0 m in Figure 10 of Teske 1991b).

The corrections are added linearly to the base case value, and may be compared with the field results in Table 1.

The swath width measurement of 250 feet in trial I3 should be carefully quantified, since it is not consistent with the sensitivity study correction. Because inwind conditions rarely exist (as do completely crosswind conditions), it should be anticipated that this value of swath width will not be realized in most field applications. Rather, swath widths for the DC-3 spraying under the conditions tested are probably more like 210 to 220 feet.

The three boom dissection studies confirm the predictions of the AGDISP model as to where the released spray material actually travels. The center boom nozzles are most distant from the wing tip vortices; their larger VMDs suggest that the vortices do not disperse spray material as much as when the spray is released midboom and boom end. The swirling vortical motion is responsible for filling the center of the spray deposition pattern when the center nozzles are disabled. These findings suggest that nozzles can be relocated from beneath the fuselage to the boom ends to increase swath width. However, off-target drift could impact the use of this approach.

These results confirm the predictions of the AGDISP model for DC-3 swath width and its sensitivity to field conditions and nozzle location.

As a part of the field trials, cards were also positioned parallel to the aircraft flight path. This data would then reflect the level of variation in deposition at a specific distance from the centerline of the aircraft. This variation could be referenced to the atmospheric turbulence level at the time of the field trials, and conclusions could be drawn. Table 2 presents the results of this study.

Each variation line was examined separately by computing the relative standard deviation RSD of the number and volume deposition levels D_i

$$RSD = \frac{1}{\overline{D}}\left(\frac{1}{N}\sum\left(D_i - \overline{D}\right)^2\right)^{1/2}$$

where

$$\overline{D} = \frac{1}{N}\sum D_i = \text{average value}$$

the index i denotes each deposition data entry and N denotes the total number of data points considered. A set of data well-approximated by its mean might have a relative standard deviation as high as 0.1. All values in the field trials are higher than this criterion.

Table 2 also shows greater variation for volume deposition than for number deposition. Since the Swathkit counts the drops and their sizes and then converts to volume, this exercise would necessarily increase the RSD. An analytical treatment is not possible here; rather, we may examine the simple series of integers [0, 1, 2, 3, ... , 100] and generate its mean (50.0) and RSD (0.583). If we now cube this series (in effect moving from the size of each drop to the volume of each drop), we recover the series [0, 1, 8, 27, ... , 1000000] and generate its mean (252500.0) and RSD (1.139). A ratio of the two RSD values gives 1.95, a number consistent with the increase in RSD in Table 2 for volume deposition over number deposition.

The atmospheric turbulence level may be obtained from the Swathkit wind speed and direction data by applying the unit vector approach of Haugen 1963. Mean horizontal wind speed $\overline{U}$ is determined from the equation

$$\overline{U} = \frac{1}{N}\sum U_i$$

where the index i denotes each meteorological data entry and N denotes the total number of data points considered. Mean wind direction $\overline{\Theta}$ and azimuthal standard deviation σ_A are found by defining

$$\overline{X} = \frac{1}{N}\sum \cos\Theta_i$$

$$\overline{Y} = \frac{1}{N}\sum \sin\Theta_i$$

for each wind direction Θ_i to obtain

$$\overline{\Theta} = \arctan\left[\frac{\overline{Y}}{\overline{X}}\right]$$

and

$$\sigma_A = \arcsin\left[\left(1 - \overline{X}^2 - \overline{Y}^2\right)^{1/2}\right]$$

These results are also shown in Table 2, and exhibit large but consistent values (consistent with the recorded time of day). Generally, the USDA Forest Service recommends spraying in the early morning hours; the azimuthal standard deviation (or, by inference, the relative turbulence level in the atmosphere) will then be below 0.1 and an axially uniform ground deposition pattern will result. As the sun rises further above the horizon, turbulent activity increases and the azimuthal standard deviation increases. Atmospheric activity generally peaks near 2 PM. The RSD values reflect conditions from the background atmosphere (in the azimuthal standard deviation) and potentially a significant level of activity from the aircraft wake itself, particularly for larger aircraft such as the DC-3. Thus, the variation levels shown here are within reach of reality.

Two important points should be considered: (1) the increased turbulence level will generally spread the spray, hence the largest swath width in trial I3 at midafternoon; and (2) typical spraying times will be much earlier than tested, hence the swath width will almost certainly be smaller than the levels achieved during the present field trials.

A detailed analysis of axial card line variation must await future work with an appropriate data base (such as Taylor et al 1972). For the present the best approach may be to consider the problem from a statistical viewpoint.

A fairly standard statistical approach to evaluating how closely the field data mean value estimates the actual mean value is to generate confidence intervals around the mean. Confidence intervals use the Student t distribution statistic (assuming a normal distribution) and are a function of the number of samples taken and the measured standard deviation (Guttman, Wilks and Hunter 1971, although any good statistics textbook will do). Confidence intervals are chosen before analyzing the data, and are based on how certain we want to be that the interval range around the data mean includes the actual mean. A typical confidence interval for field data might be 90 percent, which means that nine times out of ten the actual mean will be included in the interval range around the data mean.

In this approach we develop the normalized mean value of the swath width from the expression

$$\text{Mean Value} = 1.0 \pm t(N-1;\alpha/2)\,\frac{RSD}{\sqrt{N}}$$

where α is the confidence parameter generating the $100(1-\alpha)$ percent confidence interval, N is the number of samples (cards in this case) and t is the Student t distribution (a tabulated function). A 90 percent confidence interval is achieved with $\alpha = 0.1$. The above expression can then be used to generate the interval range (the second term on the right hand side of the above equation).

Results are plotted in Figure 1, and may be explained as follows. An interval range of 0.2 (implying that the actual mean will be within 20 percent of the data mean) can be achieved for an RSD of 0.1 with three card lines and an RSD of 0.4 with 15 card lines (for 90 percent confidence). In the field trials three card lines were averaged to represent the spray profile. Figure 1 shows that for the RSDs given in Table 2 the actual mean value (or swath width) is therefore known with very little precision (the results are near or above an interval range of 1.0). Only by conducting field tests in the early morning hours will RSD values fall to sufficiently low levels that three card lines will give a reasonable interval range on the data collected. To be 90 percent confident that the actual mean is within a 20 percent interval range around the data mean when the RSD value is equal to the average of the field trials (0.80) would have required more than 40 card rows.

If we make the assumption that the DC-3 swath width is invariant with application, then instead of looking at five sets of three card lines, we may examine one set of 15 card lines. A 90 percent confidence interval around the resulting data mean gives the normalized interval range of 0.36, which becomes

$$137 \text{ feet} < \text{DC-3 Swath Width} < 291 \text{ feet}$$

The 90 percent confidence interval provides an interval range within which the actual mean is expected 90 percent of the time. However, the data mean itself still provides the best estimate of the actual mean and is the value that should be used to represent the actual mean. Thus

$$\text{DC-3 Swath Width} = 214 \text{ feet}$$

is the principal result of the field trials.

Estimates of the actual mean become more precise (with smaller interval range) as the number of independent samples is increased (by taking more data) or when acquiring data that has a smaller standard deviation (by field testing in the early morning hours).

Vortex Panels

When the field trials repositioned spray nozzles out to 90 percent of the wing semispan, the aircraft was also fitted with vertical panels, below the wing and parallel to the longitudinal axis of the aircraft, in an attempt to observe the effect of these panels upon the spray deposition profile.

Plates positioned near the wing tips (for instance the winglets on all later copies of the Boeing 747 aircraft) essentially prevent flow around the end of the wing and thus tend to flatten the wing load distribution. The wing becomes more uniformly (rectangularly) loaded. Transition from an elliptically loaded wing to a rectangularly loaded wing is shown in Figure 2. An elliptically loaded wing distribution tends to roll into vortices centered at the (theoretical) position $\pi/4$, or 0.785, of the wing semispan (this is why spray booms should not extend beyond 75 percent of the wing semispan). As a rectangularly loaded wing distribution is approached, the centers of the vortices move toward the wing tips. Vortex plates are added to an aircraft to refine the wing load distribution shape slightly (toward a more uniform shape), leading to a slight reduction in induced drag on the aircraft (a one percent reduction in drag nonetheless saves a considerable amount of fuel in a Boeing 747). In the case of the DC-3, the vortex panels must be positioned carefully to avoid increasing the drag, and probably result in marginal improvement of overall aircraft characteristics. The vortex panels may have moved the vortices more toward the wing tips and may have reduced drift slightly from the cases without vortex panels. Also, the panels may not have been of sufficient size or in the most optimum position to achieve any real improvement in aircraft performance or spray deposition profile swath width, a conclusion confirmed by the field data.

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Table 1: Sensitivity Study Corrections to DC-3 Field Trial Conditions

Spray Trial Designation	I1	I3	E1	E2	E3	Ave
SPRAY CONDITIONS:						
Relative Humidity (percent)	75	70	68	66	61	
Release Height (feet)	125	125	125	50	50	
Boom Width (percent)	75	75	90	90	90	
Wind Speed (mph)	1.4	2.3	6.3	6.9	6.7	
Wind Direction (deg)	236	114	233	203	214	
Card Line Orientation (deg)	200	200	330	330	330	
CORRECTIONS (m):						
Relative Humidity	0.9	0.3	0.2	0.1	-0.2	
Release Height	2.6	2.6	2.6	-5.0	-5.0	
Boom Width	0.0	0.0	9.2	9.2	9.2	
Wind Direction	-5.2	-0.6	-2.6	-9.7	-9.7	
Wind Speed	0.0	0.0	0.0	10.0	2.0	
SWATH WIDTH (m):	58.9	62.9	70.0	65.2	56.9	
SWATH WIDTH (feet):	193	206	230	214	187	206
FIELD RESULTS (feet):	200	250	220	200	200	214

Table 2: Statistical Analysis of Variation Line Data

Spray Trial Designation	I1	I3	E1	E2	E3	Ave
MEAN VALUES:						
Number Deposition (drops/sq cm)						
Variation Line 1		9.44	2.98	9.42	3.94	
Variation Line 2	6.05	12.64	5.79	5.97	1.53	
Volume Deposition (IU/sq cm)						
Variation Line 1		567.19	306.78	430.39	22.65	
Variation Line 2	358.26	406.17	197.95	365.75	7.46	
RELATIVE STANDARD DEVIATIONS:						
Number Deposition						
Variation Line 1		0.36	0.54	0.33	0.49	
Variation Line 2	0.40	0.44	0.39	0.66	0.65	0.49
Volume Deposition						
Variation Line 1		0.74	0.65	0.55	0.60	
Variation Line 2	0.57	1.11	0.75	1.20	0.78	0.80
AZIMUTHAL STANDARD DEVIATIONS:	1.22	0.51	0.27	0.35	0.38	0.65
TIME OF DAY (hrs:min)	13:23	14:09	09:20	09:45	10:14	

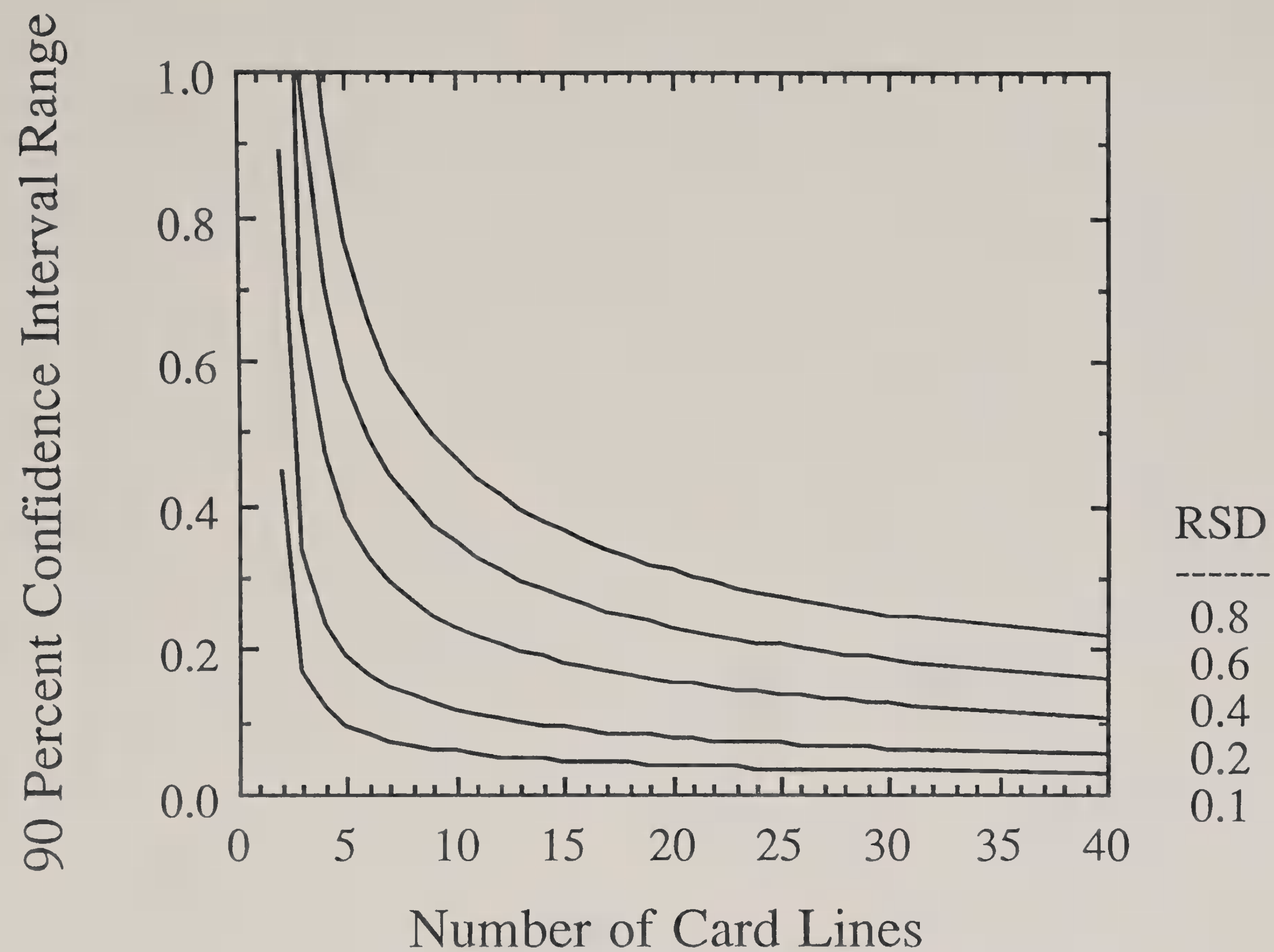

Figure 1: Student t distribution results for 90 percent confidence intervals

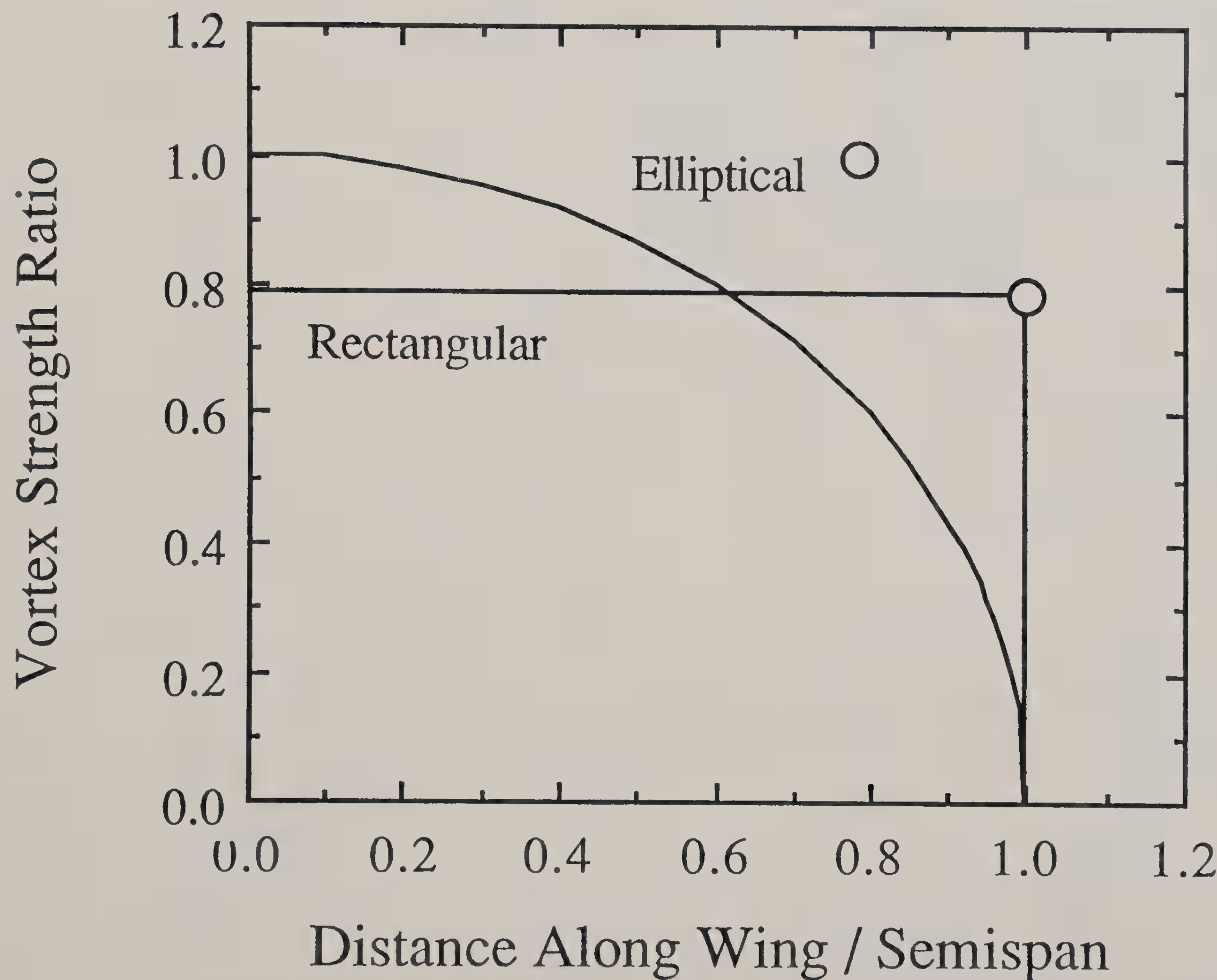

Figure 2: Aircraft wing load distributions and wing tip vortex behavior